Massive Neutrinos and Lepton Mixing, Searches for

SEARCHES FOR MASSIVE NEUTRINOS

Revised April 2000 by D.E. Groom (LBNL).

Searches for massive neutral leptons and the effects of nonzero neutrino masses are listed here. These results are divided into the following main sections:

A. Heavy neutral lepton mass limits;
B. Sum of neutrino masses;
C. Searches for neutrinoless double-β decay (see the note by P. Vogel on "Searches for neutrinoless double-β decay" preceding this section);
D. Other bounds from nuclear and particle decays;
E. Solar ν experiments (see the note on "Solar Neutrinos" by K. Nakamura preceding this section);
F. Astrophysical neutrino observations;
G. Reactor $\overline{\nu}_e$ disappearance experiments;
H. Accelerator neutrino appearance experiments;
I. Disappearance experiments with accelerator and radioactive source neutrinos.

Direct searches for masses of dominantly coupled neutrinos are listed in the appropriate sections on ν_e, ν_μ, or ν_τ, where it is assumed that the mass eigenstates ν_1, ν_2, and ν_3 predominately couple to ν_e, ν_μ, and ν_τ, respectively. Note that the assumptions made in these Listings, that ν_2 predominately couples to ν_μ and ν_3 to ν_τ, may not be true. Searches for massive charged leptons are listed elsewhere, and searches for the mixing of $(\mu^- e^+)$ and $(\mu^+ e^-)$ are given in the muon Listings.

Discussion of the current neutrino mass limits and the theory of mixing are given in the note on "Neutrino Mass" by Boris Kayser just before the ν_e Listings.

In many of the following Listings (*e.g.* neutrino disappearance and appearance experiments), results are presented assuming that mixing occurs only between two neutrino species, such as $\nu_\tau \leftrightarrow \nu_e$. This assumption is also made for lepton-number violating mixing between two states, such as $\nu_e \leftrightarrow \overline{\nu}_\mu$ or $\nu_\mu \leftrightarrow \overline{\nu}_\mu$. As discussed in Kayser's review, the assumption of mixing between only two states is valid if (a) all mixing angles are small or (b) there is a mass hierarchy such that one ΔM^2_{ij}, *e.g.* $\Delta M^2_{21} = M^2_{\nu_2} - M^2_{\nu_1}$, is small compared with the others, so that there is a region in L/E (the ratio of the distance L that the neutrino travels to its energy E) where $\Delta M^2_{21} L/E$ is negligible, but $\Delta M^2_{32} L/E$ is not.

In this case limits or results can be shown as allowed regions on a plot of $|\Delta M^2|$ as a function of $\sin^2 2\theta$. The simplest situation occurs in an "appearance" experiment, where one searches for interactions by neutrinos of a variety not expected in the beam. An example is the search for ν_e interactions in a detector in a ν_μ beam. For oscillation between two states, the probability that the "wrong" state will appear is given by Eq. 11 in Kayser's review, which may be written as

$$P = \sin^2 2\theta \, \sin^2(1.27 \Delta M^2 L/E) \ , \tag{1}$$

where $|\Delta M^2|$ is in eV^2 and L/E is in km/GeV or m/MeV. In a real experiment L and E have some spread, so that one must average P over the distribution of L/E. As an example, let us make the somewhat unrealistic assumption that $b \equiv 1.27 L/E$

has a Gaussian distribution with standard deviation σ_b about a central value b_0. Then:

$$\langle P\rangle = \frac{1}{2}\sin^2 2\theta[1 - \cos(2b_0\Delta M^2)\exp(-2\sigma_b^2(\Delta M^2)^2)] \qquad (2)$$

The value of $\langle P\rangle$ is set by the experiment. For example, if 230 interactions of the expected flavor are detected and none of the wrong flavor are seen, then $P = 0.010$ at the 90% CL.* We can then solve the above expression for $\sin^2 2\theta$ as a function of $|\Delta M^2|$. This function is shown in Fig. 1.† Note that:

(a) since the fast oscillations are completely washed out by the resolution for large $|\Delta M^2|$, $\sin^2 2\theta = 2\,\langle P\rangle$ in this region (If b is taken as much smaller than experimental resolution, Eq. (2) can be used in Monte Carlo calculations to avoid the pathology if Eq. (1) at large $\varDelta m^2$);

(b) the maximum excursion of the curve to the left is to $\sin^2 2\theta = \langle P\rangle$ with good resolution, with smaller excursion for worse resolution. This "bump" occurs at $|\Delta M^2| = \pi/2b_0$ eV^2;

(c) for large $\sin^2 2\theta$, $\Delta M^2 \approx (\langle P\rangle\,/\sin^2 2\theta)^{1/2}/b_0$; and, consequently,

(d) the intercept at $\sin^2 2\theta = 1$ is at $\Delta M^2 = \sqrt{\langle P\rangle}/b_0$.

The intercept for large $|\Delta M^2|$ is a measure of running time and backgrounds, while the intercept at $\sin^2 2\theta = 1$ depends also on the mean value of L/E. The wiggles depend on experimental features such as the size of the source, the neutrino energy distribution, and detector and analysis features. Aside from such details, the two intercepts completely describe the exclusion region: For large $|\Delta M^2|$, $\sin^2 2\theta$ is constant and equal to $2\,\langle P\rangle$, and for large $\sin^2 2\theta$ the slope is known from the intercept. For these reasons, it is (nearly) sufficient to summarize the results of an experiment by stating the two intercepts, as is done in the following tables. The reader is referred to the original papers for the two-dimensional plots expressing the actual limits.

If a positive effect is claimed, then the excluded region is replaced by an allowed band or allowed regions. This is the case for the LSND experiment [2] and the SuperKamiokande analysis of $\mathrm{R}(\mu/e)$ for atmospheric neutrinos [3].

In a "disappearance" experiment, one looks for the attenuation of the beam neutrinos (for example, ν_k) by mixing with at least one other neutrino eigenstate. (We label such experiments as $\nu_k \not\to \nu_k$.) The probability that a neutrino remains the same neutrino from the production point to detector is given by

$$P(\nu_k \to \nu_k) = 1 - P(\nu_k \to \nu_j) \ , \tag{3}$$

where mixing occurs between the kth and jth species with $P(\nu_k \to \nu_j)$ given by Eq. (1) or Eq. (2).

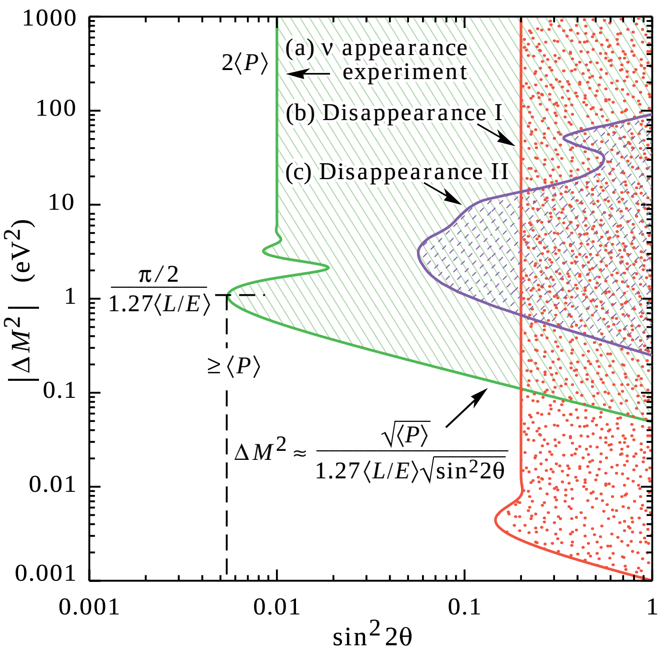


Figure 1: Neutrino oscillation parameter ranges excluded by two hypothetical experiments
(a and b) described by Eq. (2) and one real one (c). Parameters for the first two cases are given in the footnotes. In case (a) one searches for the appearance of neutrinos not expected in the beam. The probability of appearance, in this case 0.5% at some specified CL, is set by the number of right-flavor events observed and/or information about the flux and cross sections. Case (b) represents a disappearance experiment in which the flux is known in the absence of mixing. In case (c), the information comes from measured fluxes at two distances from the target [4].

In contrast to the detection of even a few "wrong-flavor" neutrinos establishing mixing in an appearance experiment, the disappearance of a few "right-flavor" neutrinos in a disappearance experiment goes unobserved because of statistical fluctuations. For this reason, disappearance experiments usually cannot establish small-probability (small $\sin^2 2\theta$) mixing.

Disappearance experiments fall into two general classes:

I. Those in which the beam neutrino flux is known, from theory or from other measurements. Examples are reactor $\overline{\nu}_e$ experiments and certain accelerator experiments. Although such experiments cannot establish very small-$\sin^2 2\theta$ mixing, they can establish small limits on ΔM^2 for large $\sin^2 2\theta$ because L/E can be very large. An example, based on the Chooz reactor measurements [5], is labeled "Disappearance I" in Fig. 1.‡

II. Those in which attenuation or oscillation of the beam neutrino flux is measured in the apparatus itself (two detectors, or a "long" detector). Above some minimum $|\Delta M^2|$ the equilibrium is established upstream, and there is no change in intensity over the length of the apparatus. As a result, sensitivity is lost at high $|\Delta M^2|$, as can be seen by the curve labeled "Disappearance II" in Fig. 1 [4]. Such experiments have not been competititive for a long time. However, a new generation of long-baseline experiments with a "near" detector and a "far" detector with very large L, *e.g.*, MINOS, will be able to use this strategy to advantage.

Finally, there are more complicated cases, such as analyses of solar neutrino data in terms of the MSW parameters [6]. For a variety of physical reasons, an irregular region in the $|\Delta M^2|$ vs $\sin^2 2\theta$ plane is allowed. It is difficult to represent these graphical data adequately within the strictures of our tables.

Experimental two-neutrino mixing limits and positive signals are shown on the following page.

Footnotes and References

* A superior statistical analysis of confidence limits in the $\sin^2 2\theta$–$|\Delta M^2|$ plane is given in Ref. 1.

† Curve generated with $\langle P\rangle = 0.005$, $\langle L/E\rangle = 1.11$, and $\sigma_b/b_0 = 0.08$.

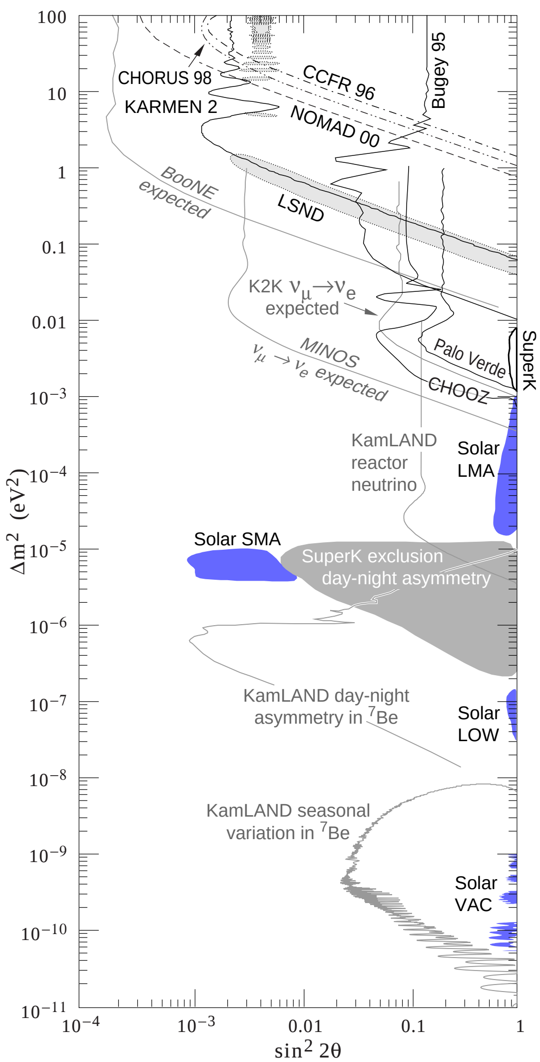
‡ Curve parameters $\langle P\rangle = 0.1$, $\langle L/E\rangle = 237$, and $\sigma_b/b_0 = 0.5$. For the actual Chooz experiment [5], $\langle L/E\rangle \approx 300$ and the limit on $\langle P\rangle$ is 0.09.

1. G.J. Feldman and R.D. Cousins, Phys. Rev. **D3873** (1998).
2. C. Athanassopoulos *et al.*, Phys. Rev. **C54** (1996).
3. Y. Fukuda *et al.*, eprint `hep-ex/9803005`.
4. F. Dydak *et al.*, Phys. Lett. **134B** (1984).
5. M. Apollonio *et al.*, Phys. Lett. **B420**, 397 (1998).
6. N. Hata and P. Langacker, Phys. Rev. **D56**, 6107 (1997).

Citation: D.E. Groom *et al.* (Particle Data Group), Eur. Phys. Jour. **C15**, 1 (2000) (URL: http://pdg.lbl.gov)

TWO-FLAVOR OSCILLATION PARAMETERS AND LIMITS

Written April 2000 by H. Murayama (LBNL).



Citation: D.E. Groom *et al.* (Particle Data Group), Eur. Phys. Jour. **C15**, 1 (2000) (URL: http://pdg.lbl.gov)

Figure 1: The most important exclusion limits as well as preferred parameter regions from neutrino oscillation experiments in the context of two-flavor oscillations. Beware that the plot shows oscillation modes on different pairs of neutrinos at the same time. All of them are 90% confidence limits unless otherwise noted. From the top,

- CCFR 96 limit is on ν_μ to ν_e oscillation from ROMOSAN 97
- KARMEN 2 excluded region and LSND preferred region are for $\bar{\nu}_e$ appearance from $\bar{\nu}_\mu$ taken from Klaus Eitel, New J. Phys. **2**, 1 (2000), Fig. 12
- Bugey 95 limit is on $\bar{\nu}_e$ disappearance from ACHKAR 95
- CHOOZ limit is on $\bar{\nu}_e$ disappearance from APOLLONIO 99, Fig. 9
- Palo Verde limit is on $\bar{\nu}_e$ disappearance from BOEHM 00, Fig. 3, curve (b)
- SuperKamiokande preferred region is on $\overset{(-)}{\nu}_\mu$ disappearance from FUKUDA 98C
- Solar neutrino preferred regions (solar LMA, solar SMA, solar LOW, and solar VAC) are on ν_e disappearance from J.N. Bahcall, P.I. Krastev, and A.Yu. Smirnov, Phys. Rev. **D58**, 096016 (1998) based on solar neutrino rates only at 99% CL
- SuperKamiokande exclusion is based on the absence of day-night asymmetry in the neutrino rate from FUKUDA 99, Fig. 2, at 99% CL
- Some projected improvements by near-future experiments on ν_e oscillations are shown in grey

Note that the plot shows only half of the parameter space $\Delta m^2 \cos 2\theta > 0$, while the other half $\Delta m^2 \cos 2\theta < 0$ should show different regions excluded/preferred, especially for solar neutrino oscillations (de Gouvêa *et al.*, `hep-ph/0002064`) once experiments report their data. References in upper-case letters are given at the end of the Listings for "Massive Neutrinos and Lepton Mixing."

(A) Heavy neutral leptons

Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with $m<$ 2400 GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.0	95	ABREU	92B	DLPH	Dirac
>39.5	95	ABREU	92B	DLPH	Majorana
>44.1	95	ALEXANDER	91F	OPAL	Dirac
>37.2	95	ALEXANDER	91F	OPAL	Majorana
none 3–100	90	SATO	91	KAM2	Kamiokande II
>42.8	95	[1] ADEVA	90S	L3	Dirac
>34.8	95	[1] ADEVA	90S	L3	Majorana
>42.7	95	DECAMP	90F	ALEP	Dirac

[1] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 >$ 6.2×10^{-8} at $m_{L^0} = 20$ GeV and $>$ 5.1×10^{-10} for m_{L^0} = 40 GeV.

Neutral Heavy Lepton MASS LIMITS

Limits apply only to heavy lepton type given in comment at right of data Listings. See review above for description of types.

See the "Quark and Lepton Compositeness, Searches for" Listings for limits on radiatively decaying excited neutral leptons, *i.e.* $\nu^* \rightarrow \nu\gamma$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>76.5	95	ABREU	99O	DLPH	Dirac coupling to e
>79.5	95	ABREU	99O	DLPH	Dirac coupling to μ
>60.5	95	ABREU	99O	DLPH	Dirac coupling to τ
>92.4	95	ACCIARRI	99L	L3	Dirac coupling to e
>81.8	95	ACCIARRI	99L	L3	Majorana coupling to e
>93.3	95	ACCIARRI	99L	L3	Dirac coupling to μ
>84.1	95	ACCIARRI	99L	L3	Majorana coupling to μ
> 83.3	95	ACCIARRI	99L	L3	Dirac coupling to τ
> 73.5	95	ACCIARRI	99L	L3	Majorana coupling to τ
>69.8	95	[2] ACKERSTAFF	98C	OPAL	Majorana, coupling to e
>79.1	95	[2] ACKERSTAFF	98C	OPAL	Dirac, coupling to e
>68.7	95	[2] ACKERSTAFF	98C	OPAL	Majorana, coupling to μ
>78.5	95	[2] ACKERSTAFF	98C	OPAL	Dirac, coupling to μ
>54.4	95	[2] ACKERSTAFF	98C	OPAL	Majorana, coupling to τ
>69.0	95	[2] ACKERSTAFF	98C	OPAL	Dirac, coupling to τ
>63	95	[3,4] BUSKULIC	96S	ALEP	Dirac
>54.3	95	[3,5] BUSKULIC	96S	ALEP	Majorana

[2] The decay length of the heavy lepton is assumed to be $<$ 1 cm, limiting the square of the mixing angle $|U_{\ell j}|^2$ to 10^{-12}.

[3] BUSKULIC 96S requires the decay length of the heavy lepton to be $<$ 1 cm, limiting the square of the mixing angle $|U_{\ell j}|^2$ to 10^{-10}.

[4] BUSKULIC 96S limit for mixing with τ. Mass is $>$ 63.6 GeV for mixing with e or μ.

[5] BUSKULIC 96S limit for mixing with τ. Mass is $>$ 55.2 GeV for mixing with e or μ.

Astrophysical Limits on Neutrino MASS for m_ν > 1 GeV

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 60–115		[6] FARGION	95	ASTR	Dirac
none 9.2–2000		[7] GARCIA	95	COSM	Nucleosynthesis
none 26–4700		[7] BECK	94	COSM	Dirac
none 6 – hundreds		[8,9] MORI	92B	KAM2	Dirac neutrino
none 24 – hundreds		[8,9] MORI	92B	KAM2	Majorana neutrino
none 10–2400	90	[10] REUSSER	91	CNTR	HPGe search
none 3–100	90	SATO	91	KAM2	Kamiokande II
		[11] ENQVIST	89	COSM	
none 12–1400		[7] CALDWELL	88	COSM	Dirac ν
none 4–16	90	[7,8] OLIVE	88	COSM	Dirac ν
none 4–35	90	OLIVE	88	COSM	Majorana ν
>4.2 to 4.7		SREDNICKI	88	COSM	Dirac ν
>5.3 to 7.4		SREDNICKI	88	COSM	Majorana ν
none 20–1000	95	[7] AHLEN	87	COSM	Dirac ν
>4.1		GRIEST	87	COSM	Dirac ν

[6] FARGION 95 bound is sensitive to assumed ν concentration in the Galaxy. See also KONOPLICH 94.

[7] These results assume that neutrinos make up dark matter in the galactic halo.

[8] Limits based on annihilations in the sun and are due to an absence of high energy neutrinos detected in underground experiments.

[9] MORI 92B results assume that neutrinos make up dark matter in the galactic halo. Limits based on annihilations in earth are also given.

[10] REUSSER 91 uses existing $\beta\beta$ detector (see FISHER 89) to search for CDM Dirac neutrinos.

[11] ENQVIST 89 argue that there is no cosmological upper bound on heavy neutrinos.

(B) Sum of neutrino masses

Revised April 1998 by K.A. Olive (University of Minnesota).

The limits on low mass ($m_\nu \lesssim$ 1 MeV) neutrinos apply to $m_{\rm tot}$ given by

$$m_{\rm tot} = \sum_\nu (g_\nu/2) m_\nu \ ,$$

where g_ν is the number of spin degrees of freedom for ν plus $\overline{\nu}$: $g_\nu = 4$ for neutrinos with Dirac masses; $g_\nu = 2$ for Majorana neutrinos. Stable neutrinos in this mass range make a contribution to the total energy density of the Universe which is given by

$$\rho_\nu = m_{\rm tot} n_\nu = m_{\rm tot}(3/11) n_\gamma \ ,$$

where the factor 3/11 is the ratio of (light) neutrinos to photons. Writing $\Omega_\nu = \rho_\nu/\rho_c$, where ρ_c is the critical energy density of the Universe, and using $n_\gamma = 412\ {\rm cm}^{-3}$, we have

$$\Omega_\nu h^2 = m_{\rm tot}/(94\ \ {\rm eV}) \ .$$

Therefore, a limit on $\Omega_\nu h^2$ such as $\Omega_\nu h^2 < 0.25$ gives the limit

$$m_{\rm tot} < 24\ \ {\rm eV} \ .$$

The limits on high mass ($m_\nu > 1$ MeV) neutrinos apply separately to each neutrino type.

Limit on Total ν MASS, m_{tot}

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to m_{tot}. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 5.5	[12] CROFT	99	ASTR	Ly α power spec
<180	SZALAY	74	COSM	
<132	COWSIK	72	COSM	
<280	MARX	72	COSM	
<400	GERSHTEIN	66	COSM	

[12] CROFT 99 result based on the power spectrum of the Ly α forest. If $\Omega_{\rm matter} < 0.5$, the limit is improved to $m_\nu < 2.4$ ($\Omega_{\rm matter}$/0.17–1) eV.

Limits on MASSES of Light Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<100–200	[13] OLIVE	82	COSM	Dirac ν
<200–2000	[13] OLIVE	82	COSM	Majorana ν

[13] Depending on interaction strength G_R where $G_R < G_F$.

Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>$ 10	[14] OLIVE	82	COSM	G_R/G_F <0.1
$>$100	[14] OLIVE	82	COSM	G_R/G_F <0.01

[14] These results apply to heavy Majorana neutrinos and are summarized by the equation: m_ν >1.2 GeV (G_F/G_R). The bound saturates, and if G_R is too small no mass range is allowed.

(C) Searches for neutrinoless double-β decay

LIMITS FROM NEUTRINOLESS $\beta\beta$ DECAY

Revised September 1999 by P. Vogel (Caltech).

Neutrinoless double beta decay, if observed, would signal violation of the total lepton number conservation. The process can be mediated by an exchange of light Majorana neutrino, or by an exchange of other particles. As long as only a limit on its lifetime is available, limits on the effective Majorana neutrino mass, and on the lepton-number violating right-handed current admixture can be obtained, independently on the actual mechanism. These are considered in the following three tables.

The derived quantities are nuclear model-dependent, so the half-life measurements are given first. Where possible, we list the references for the nuclear matrix elements used in the subsequent analysis. Since rates for the more conventional $2\nu\beta\beta$ decay serve to calibrate the theory, results for this process are also given. As an indication of the spread among different ways of evaluating the matrix elements, we show in Fig. 1 some representative examples for the most popular nuclei.

To define the limits on lepton-number violating right-handed current admixtures, we display the relevant part of a phenomenological current-current weak interaction Hamiltonian:

$$H_W = (G_F/\sqrt{2}) \times (J_L \cdot j_L^\dagger + \kappa J_R \cdot j_L^\dagger + \eta J_L \cdot j_R^\dagger + \lambda J_R \cdot j_R^\dagger) + \text{h.c.} \qquad (1)$$

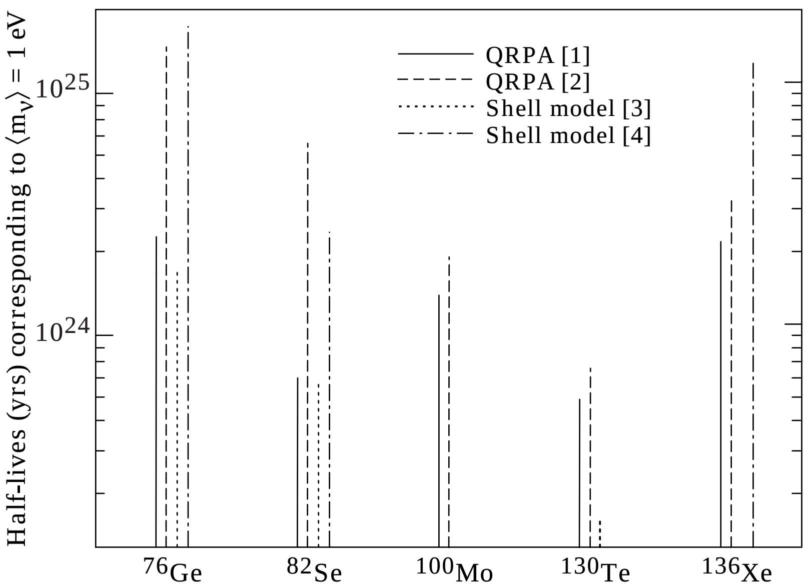


Figure 1: Half-lives (in years) calculated for $\langle m_\nu \rangle = 1$ eV by various representative methods and different authors for the most popular double-beta decay candidate nuclei. Solid lines are QRPA from [1], dashed lines are QRPA from [2] (recalculated for $g_A = 1.25$ and $\alpha' = -390$ MeV fm^3, dotted lines are shell model [3], and dot-and-dashed lines are shell model [4].

where $j_L^\mu = \bar{e}_L \gamma^\mu \nu_{eL}$, $j_R^\mu = \bar{e}_R \gamma^\mu \nu_{eR}$, and J_L^μ and J_R^μ are left-handed and right-handed hadronic weak currents. Experiments are not sensitive to κ, but quote limits on quantities proportional to η and λ.* In analogy to $\langle m_\nu \rangle$ (see Eq. 17 in the "Neutrino mass" at the beginning of the Neutrino Particle Listings), the quantities extracted from experiments are $\langle \eta \rangle = \eta \sum U_{1j} V_{1j}$ and $\langle \lambda \rangle = \lambda \sum U_{1j} V_{1j}$, where V_{ij} is a matrix analogous to U_{ij} (see Eq. 2 in the "Neutrino mass"), but describing the mixing among right-handed neutrinos. The quantities $\langle\eta\rangle$ and $\langle\lambda\rangle$ therefore vanish for massless or unmixed neutrinos. Also, as in the case of $\langle m_\nu\rangle$, cancellations are possible in $\langle\eta\rangle$ and $\langle\lambda\rangle$. The limits on $\langle\eta\rangle$ are of order 10^{-8} while the limits on $\langle\lambda\rangle$ are of order 10^{-6}. The reader is warned that a number of earlier experiments did not distinguish between η and λ. Because of evolving reporting conventions and matrix element calculations, we have not tabulated the admixture parameters for experiments published earlier than 1989.

See the section on Majoron searches for additional limits set by these experiments.

Footnotes and References

* We have previously used a less accepted but more explicit notation in which $\eta_{RL} \equiv \kappa$, $\eta_{LR} \equiv \eta$, and $\eta_{RR} \equiv \lambda$.

1. A. Staudt, K. Muto, and H.V. Klapdor-Kleingrothaus, Europhys. Lett. **13**, 31 (1990).
2. J. Engel, P. Vogel, and M.R. Zirnbauer, Phys. Rev. **C37**, 731 (1988).
3. W.C. Haxton and G.J. Stephenson Jr., Prog. in Part. Nucl. Phys. **12**, 409 (1984).
4. E. Caurier, F. Nowacki, A. Poves, and J. Retamosa Phys. Rev. Lett. **77**, 1954 (1996).

Half-life Measurements and Limits for Double β Decay

In all cases of double beta decay, (Z,A) $\rightarrow$ (Z+2,A) $+2e^-$ + (0 or 2)$\overline{\nu}_e$. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

$t_{1/2}$(10^{21} yr)	CL%	ISOTOPE		TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$>$ 8000	90	^{76}Ge	0ν		Enriched HPGe	[15] AALSETH	99
$0.021^{+0.008}_{-0.004} \pm 0.002$		^{96}Zr	2ν		NEMO-2	[16] ARNOLD	99
$>$ 1.0	90	^{96}Zr	0ν		NEMO-2	[16] ARNOLD	99
$>$ 0.39	90	^{96}Zr	0ν	$0^0 \rightarrow 2^+$	NEMO-2	[16] ARNOLD	99
$>$16000(57000)	90	^{76}Ge	0ν		Enriched HPGe	[17] BAUDIS	99B
$>$ 56	90	^{130}Te	0ν		Cryog. det.	[18] ALESSAND...	98

$>$ 16	90	^{130}Te	0ν	$0^+ \to 2^+$	Cryog. det.	[18]	ALESSAND...	98
$>$ 17	90	^{128}Te	0ν		Cryog. det.	[18]	ALESSAND...	98
$>$ 440	90	^{136}Xe	0ν		Xe TPC	[19]	LUESCHER	98
$>$ 0.36	90	^{136}Xe	2ν		Xe TPC	[20]	LUESCHER	98
$(7.6^{+2.2}_{-1.4})$E-3		^{100}Mo	2ν		Si(Li)	[21]	ALSTON-...	97
$>$ 0.19	90	^{92}Mo	0ν+2ν	$0^+ \to 0^+$	γ in HPGe	[22]	BARABASH	97
$>$ 0.81	90	^{92}Mo	0ν+2ν	$0^+ \to 0^+_1$	γ in HPGe	[22]	BARABASH	97
$>$ 0.89	90	^{92}Mo	0ν+2ν	$0^+ \to 2^+_1$	γ in HPGe	[22]	BARABASH	97
$>$11000	90	^{76}Ge	0ν	$0^+ \to 0^+$	Enriched HPGe	[23]	BAUDIS	97
$(6.82^{+0.38}_{-0.53} \pm 0.68)$E-3		^{100}Mo	2ν		TPC	[24]	DESILVA	97
$(6.75^{+0.37}_{-0.42} \pm 0.68)$E-3		^{150}Nd	2ν		TPC	[25]	DESILVA	97
$>$ 1.2	90	^{150}Nd	0ν		TPC	[26]	DESILVA	97
$1.77 \pm 0.01^{+0.13}_{-0.11}$		^{76}Ge	2ν		Enriched HPGe	[27]	GUENTHER	97
$(3.75 \pm 0.35 \pm 0.21)$E-2		^{116}Cd	2ν	$0^+ \to 0^+$	NEMO 2	[28]	ARNOLD	96
$0.043^{+0.024}_{-0.011} \pm 0.014$		^{48}Ca	2ν		TPC	[29]	BALYSH	96
$>$ 52	68	^{100}Mo	0ν,$\langle m_\nu \rangle$	$0^+ \to 0^+$	ELEGANT V	[30]	EJIRI	96
$>$ 39	68	^{100}Mo	0ν,$\langle \lambda \rangle$	$0^+ \to 0^+$	ELEGANT V	[30]	EJIRI	96
$>$ 51	68	^{100}Mo	0ν,$\langle \eta \rangle$	$0^+ \to 0^+$	ELEGANT V	[30]	EJIRI	96
0.79 ± 0.10		^{130}Te	0ν+2ν		Geochem	[31]	TAKAOKA	96
$0.61^{+0.18}_{-0.11}$		^{100}Mo	0ν+2ν	$0^+ \to 0^+_1$	γ in HPGe	[32]	BARABASH	95
$>$ 0.00013	99	^{160}Gd	2ν	$0^+ \to 0^+$	Gd_2SiO_5:Ce scint	[33]	BURACHAS	95
$>$ 0.00012	99	^{160}Gd	2ν	$0^+ \to 2^+$	Gd_2SiO_5:Ce scint	[33]	BURACHAS	95
$>$ 0.014	90	^{160}Gd	0ν	$0^+ \to 0^+$	Gd_2SiO_5:Ce scint	[33]	BURACHAS	95
$>$ 0.013	90	^{160}Gd	0ν	$0^+ \to 2^+$	Gd_2SiO_5:Ce scint	[33]	BURACHAS	95
$(9.5 \pm 0.4 \pm 0.9)$E18		^{100}Mo	2ν		NEMO 2		DASSIE	95
$>$ 0.6	90	^{100}Mo	0ν	$0^+ \to 0^+_1$	NEMO 2		DASSIE	95
$0.026^{+0.009}_{-0.005}$		^{116}Cd	2ν	$0^+ \to 0^+$	ELEGANT IV		EJIRI	95
$>$ 29	90	^{116}Cd	0ν	$0^+ \to 0^+$	$^{116}CdWO_4$ scint	[34]	GEORGADZE	95
$>$ 0.3	68	^{160}Gd	0ν		Gd_2SiO_5: Ce scint		KOBAYASHI	95
$>$ 2.37	90	^{116}Cd	0ν+2ν	$0^+ \to 2^+$	γ in HPGe	[35]	PIEPKE	94
$>$ 2.05	90	^{116}Cd	0ν+2ν	$0^+ \to 0^+_1$	γ in HPGe	[35]	PIEPKE	94
$>$ 2.05	90	^{116}Cd	0ν+2ν	$0^+ \to 0^+_2$	γ in HPGe	[35]	PIEPKE	94
$0.017^{+0.010}_{-0.005} \pm 0.0035$		^{150}Nd	2ν	$0^+ \to 0^+$	TPC		ARTEMEV	93
0.039 ± 0.009		^{96}Zr	0ν+2ν		Geochem		KAWASHIMA	93
$>$ 430	90	^{76}Ge	0ν	$0^+ \to 2^+$	Enriched HPGe		BALYSH	92
2.7 ± 0.1		^{130}Te			Geochem		BERNATOW...	92
7200 ± 400		^{128}Te			Geochem	[36]	BERNATOW...	92
$>$ 27	68	^{82}Se	0ν	$0^+ \to 0^+$	TPC		ELLIOTT	92
$0.108^{+0.026}_{-0.006}$		^{82}Se	2ν	$0^+ \to 0^+$	TPC		ELLIOTT	92
$0.92^{+0.07}_{-0.04}$		^{76}Ge	2ν	$0^+ \to 0^+$	Enriched HPGe	[37]	AVIGNONE	91
$>$ 3.3	95	^{136}Xe	0ν	$0^+ \to 2^+$	Prop cntr	[38]	BELLOTTI	91
$>$ 0.16	95	^{136}Xe	2ν		Prop cntr		BELLOTTI	91

2.0 ± 0.6		^{238}U			Radiochem	[39] TURKEVICH	91
$>$ 9.5	76	^{48}Ca	0ν		CaF_2 scint.	YOU	91
$1.12^{+0.48}_{-0.26}$		^{76}Ge	2ν	$0^+ \rightarrow 0^+$	HPGe	[40] MILEY	90
0.9 ± 0.1		^{76}Ge	2ν		Enriched Ge(Li)	VASENKO	90
$>$ 4.7	68	^{128}Te		$0^+ \rightarrow 2^+$	Ge(Li)	[33] BELLOTTI	87
$>$ 4.5	68	^{130}Te		$0^+ \rightarrow 2^+$	Ge(Li)	[33] BELLOTTI	87
$>$ 800	95	^{128}Te			Geochem	[41] KIRSTEN	83
2.60 ± 0.28		^{130}Te			Geochem	[41] KIRSTEN	83

[15] AALSETH 99 limit is based on 74.84 active mol-yr of data using enriched Ge detectors at several locations. It is not competive with BAUDIS 99B.

[16] ARNOLD 99 measure directly the 2ν decay of Zr for the first time, using the NEMO-2 tracking detector and an isotopically enriched source. The lifetime is more accurate than the geochemical result of KAWASHIMA 93.

[17] BAUDIS 99B is a continuation of the work of BAUDIS 97. The limit is based on a subset of data using a pulse shape event selection. The exposure time is 24.2 kg-yr. The more stringent limit, in parentheses, results from unphysical data (measured rate significantly below expected background), while the smaller value is the experimental sensitivity as defined by FELDMAN 98. This work supersedes BAUDIS 97 as the most stringent result.

[18] ALESSANDRELLO 98 report limits using an array of 20 cryogenic detectors of 340 grams of TeO_2 each. Supersedes ALESSANDRELLO 96B.

[19] LUESCHER 98 report a limit for the 0ν decay of ^{136}Xe TPC. Supersedes VUILLEUMIER 93.

[20] LUESCHER 98 report a limit for the 2ν decay of ^{136}Xe using Xe TPC. Supersedes VUILLEUMIER 93.

[21] ALSTON-GARNJOST 97 report evidence for 2ν decay of ^{100}Mo. This decay has been also observed by EJIRI 91, DASSIE 95, and DESILVA 97.

[22] BARABASH 97 measure limits for β^+, EC, and ECEC decay of ^{92}Mo to the ground and excited states of ^{92}Ru, respectively. Limits are not competive compared to $\beta^-\beta^-$ searches as far as sensitivity to $\langle m_\nu \rangle$ or RHC admixtures is concerned.

[23] BAUDIS 97 limit for 0ν decay of enriched ^{76}Ge using Ge calorimeters supersedes GUENTHER 97.

[24] DESILVA 97 result for 2ν decay of ^{100}Mo is in agreement with ALSTON-GARNJOST 97 and DASSIE 95. This measurement has the smallest errors.

[25] DESILVA 97 result for 2ν decay of ^{150}Nd is in marginal agreement with ARTEMEV 93. It has smaller errors.

[26] DESILVA 97 do not explain whether their efficiency for 0ν decay of ^{150}Nd was calculated under the assumption of a $\langle m_\nu \rangle$, $\langle \lambda \rangle$, or $\langle \eta \rangle$ driven decay.

[27] GUENTHER 97 half-life for the 2ν decay of ^{76}Ge is not in good agreement with the previous measurements of BALYSH 94, AVIGNONE 91, and MILEY 90.

[28] ARNOLD 96 measure the 2ν decay of ^{116}Cd. This result is in agreement with EJIRI 95, but has smaller errors. Supersedes ARNOLD 95.

[29] BALYSH 96 measure the 2ν decay of ^{48}Ca, using a passive source of enriched ^{48}Ca in a TPC.

[30] EJIRI 96 use energy and angular correlations of the 2β-rays in efficiency estimate to give limits for the 0ν decay modes associated with $\langle m_\nu \rangle$, $\langle \lambda \rangle$, and $\langle \eta \rangle$, respectively. Enriched ^{100}Mo source is used in tracking calorimeter. These are the best limits for ^{100}Mo. Limit is more stringent than ALSTON-GARNJOST 97.

[31] TAKAOKA 96 measure the geochemical half-life of ^{130}Te. Their value is in disagreemnt with the quoted values of BERNATOWICZ 92 and KIRSTEN 83; but agrees with several other unquoted determinations, e.g., MANUEL 91.

[32] BARABASH 95 cannot distinguish 0ν and 2ν, but it is inferred indirectly that the 0ν mode accounts for less than 0.026% of their event sample. They also note that their result disagrees with the previous experiment by the NEMO group (BLUM 92).

[33] BELLOTTI 87 searches for γ rays for 2^+ state decays in corresponding Xe isotopes. Limit for ^{130}Te case argues for dominant $0^+ \rightarrow 0^+$ transition in known decay of this isotope.

[34] GEORGADZE 95 result for this and other modes are also give in DANEVICH 95. Result for 2ν decay omitted because of authors' caveats.

[35] In PIEPKE 94, the studied excited states of ^{116}Sn have energies above the ground state of 1.2935 MeV for the 2^+ state, 1.7568 MeV for the 0^+_1 state, and 2.0273 for the 0^+_2 state.

[36] BERNATOWICZ 92 finds ^{128}Te/^{130}Te activity ratio from slope of ^{128}Xe/^{132}Xe vs ^{130}Xe/^{132}Xe ratios during extraction, and normalizes to lead-dated ages for the ^{130}Te lifetime. The authors state that their results imply that "(a) the double beta decay of ^{128}Te has been firmly established and its half-life has been determined . . . without any ambiguity due to trapped Xe interferences. . . (b) Theoretical calculations . . . underestimate the [long half-lives of ^{128}Te ^{130}Te] by 1 or 2 orders of magnitude, pointing to a real supression in the 2ν decay rate of these isotopes. (c) Despite [this], most $\beta\beta$-models predict a *ratio* of 2ν decay widths . . . in fair agreement with observation." Further details of the experiment are given in BERNATOWICZ 93. Our listed half-life has been revised downward from the published value by the authors, on the basis of reevaluated cosmic-ray ^{128}Xe production corrections.

[37] AVIGNONE 91 reports confirmation of the MILEY 90 and VASENKO 90 observations of $2\nu\beta\beta$ decay of ^{76}Ge. Error is 2σ.

[38] BELLOTTI 91 uses difference between natural and enriched ^{136}Xe runs to obtain $\beta\beta0\nu$ limits, leading to "less stringent, but safer limits."

[39] TURKEVICH 91 observes activity in old U sample. The authors compare their results with theoretical calculations. They state "Using the phase-space factors of Boehm and Vogel (BOEHM 87) leads to matrix element values for the ^{238}U transition in the same range as deduced for ^{130}Te and ^{76}Ge. On the other hand, the latest theoretical estimates (STAUDT 90) give an upper limit that is 10 times lower. This large discrepancy implies either a defect in the calculations or the presence of a faster path than the standard two-neutrino mode in this case." See BOEHM 87 and STAUDT 90.

[40] MILEY 90 claims only "suggestive evidence" for the decay. Error is 2σ.

[41] KIRSTEN 83 reports "2σ" error. References are given to earlier determinations of the ^{130}Te lifetime.

$\langle m_\nu \rangle$, The Effective Weighted Sum of Majorana Neutrino Masses Contributing to Neutrinoless Double β Decay

$\langle m_\nu \rangle = \left|\Sigma\ U^2_{1j} m_{\nu_j}\right|$, where the sum goes from 1 to *n* and where $n =$ number of neutrino generations, and ν_j is a Majorana neutrino. Note that U^2_{ej}, not $\left|U_{ej}\right|^2$, occurs in the sum. The possibility of cancellations has been stressed. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

VALUE (eV)	*CL%*	*ISOTOPE*	*TRANSITION*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<$ 0.5–1.5	90	^{76}Ge		Enriched HPGe	[42] AALSETH	99
$<$23	90	^{96}Zr		NEMO-2	[43] ARNOLD	99
$<$ 0.4(0.2)–1.0(0.6)	90	^{76}Ge		Enriched HPGe	[44] BAUDIS	99B

$<$ 2.4–2.7	90	^{136}Xe	0ν		Xe TPC	[45] LUESCHER	98
$<$9.3	68	^{100}Mo	0ν		Si(Li)	[46] ALSTON-...	97
$<$0.46	90	^{76}Ge	0ν	$0^+ \to 0^+$	Enriched HPGe	[47] BAUDIS	97
$<$2.2	68	^{100}Mo	0ν	$0^+ \to 0^+$	ELEGANT V	[48] EJIRI	96
$<$4.1	90	^{116}Cd	0ν		$^{116}CdWO_4$ scint	[49] DANEVICH	95
$<$ 2.8–4.3	90	^{136}Xe	0ν	$0^+ \to 0^+$	TPC	[50] VUILLEUMIER	93
$<$ 1.1–1.5		^{128}Te			Geochem	[51] BERNATOW...	92
$<$5	68	^{82}Se			TPC	[52] ELLIOTT	92
$<$8.3	76	^{48}Ca	0ν		CaF_2 scint.	YOU	91
$<$5.6	95	^{128}Te			Geochem	KIRSTEN	83

[42] In AALSETH 99, the range given in the limit reflects the spread of the corresponding nuclear matrix elements. This limit is not competive with BAUDIS 99B.

[43] ARNOLD 99 limit based on the nuclear matrix elements of STAUDT 90.

[44] BAUDIS 99B derive a limit for $\langle m_\nu \rangle$ using the matrix elements of STAUDT 90. The uncertainty given for $\langle m_\nu \rangle$ reflects theoretical uncertainty in the matrix element calculations. The less restrictive limit is based on the quoted experimental sensitivity while the lower value in parentheses makes use of measured rates significantly below background.

[45] LUESCHER 98 limit for $\langle m_\nu \rangle$ is based on the matrix elements of ENGEL 88.

[46] ALSTON-GARNJOST 97 obtain the limit for $\langle m_\nu \rangle$ using the matrix elements of ENGEL 88. The limit supersedes ALSTON-GARNJOST 93.

[47] BAUDIS 97 limit for $\langle m_\nu \rangle$ is based on the matrix elements of STAUDT 90. This is the most stringent bound on $\langle m_\nu \rangle$. It supersedes the limit of GUENTHER 97.

[48] EJIRI 96 obtain the limit for $\langle m_\nu \rangle$ using the matrix elements of TOMODA 91.

[49] DANEVICH 95 is identical to GEORGADZE 95.

[50] VUILLEUMIER 93 mass range from parameter range in the Caltech calculations (ENGEL 88). On the basis of these calculations, the BALYSH 92 mass range would be $<$ 2.2–4.4 eV.

[51] BERNATOWICZ 92 finds these majoron mass limits assuming that the measured geochemical decay width is a limit on the 0ν decay width. The range is the range found using matrix elements from HAXTON 84, TOMODA 87, and SUHONEN 91. Further details of the experiment are given in BERNATOWICZ 93.

[52] ELLIOTT 92 uses the matrix elements of HAXTON 84.

Limits on Lepton-Number Violating ($V+A$) Current Admixture

For reasons given in the discussion at the beginning of this section, we list only results from 1989 and later. $\langle \lambda \rangle = \lambda \sum U_{ej} V_{ej}$ and $\langle \eta \rangle = \eta \sum U_{ej} V_{ej}$, where the sum is over the number of neutrino generations. This sum vanishes for massless or unmixed neutrinos. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

$\langle \lambda \rangle$ (10^{-6})	CL%	$\langle \eta \rangle$ (10^{-8})	CL%	ISOTOPE	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$<$1.1	90	$<$0.64	90	^{76}Ge	Enriched HPGe	[53] GUENTHER	97
$<$3.7	68	$<$2.5	68	^{100}Mo	Elegant V	[54] EJIRI	96
$<$5.3	90	$<$5.9	90	^{116}Cd	$^{116}CdWO_4$ scint	[55] DANEVICH	95
$<$4.4	90	$<$2.3	90	^{136}Xe	TPC	[56] VUILLEUMIER	93
		$<$5.3		^{128}Te	Geochem	[57] BERNATOW...	92

[53] GUENTHER 97 limits use the matrix elements of STAUDT 90. Supersedes BALYSH 95 and BALYSH 92.

[54] EJIRI 96 obtain limits for $\langle \lambda \rangle$ and $\langle \eta \rangle$ using the matrix elements of TOMODA 91.

[55] DANEVICH 95 is identical to GEORGADZE 95.
[56] VUILLEUMIER 93 uses the matrix elements of MUTO 89.
[57] BERNATOWICZ 92 takes the measured geochemical decay width as a limit on the 0ν width, and uses the SUHONEN 91 coefficients to obtain the least restrictive limit on η. Further details of the experiment are given in BERNATOWICZ 93.

(D) Other bounds from nuclear and particle decays

Limits on $|U_{e x}|^2$ as Function of m_{ν_x}

Peak and kink search tests

Limits on $|U_{e x}|^2$ as function of m_{ν_j}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1 \times 10^{-7}$	90	[58] BRITTON	92B	CNTR	50 MeV $< m_{\nu_x} <$ 130 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5 \times 10^{-6}$	90	DELEENER-...	91		m_{ν_x}=20 MeV
$<5 \times 10^{-7}$	90	DELEENER-...	91		m_{ν_x}=40 MeV
$<3 \times 10^{-7}$	90	DELEENER-...	91		m_{ν_x}=60 MeV
$<1 \times 10^{-6}$	90	DELEENER-...	91		m_{ν_x}=80 MeV
$<1 \times 10^{-6}$	90	DELEENER-...	91		m_{ν_x}=100 MeV
$<5 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=60 MeV
$<2 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=80 MeV
$<3 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=100 MeV
$<1 \times 10^{-6}$	90	AZUELOS	86	CNTR	m_{ν_x}=120 MeV
$<2 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=130 MeV
$<1 \times 10^{-4}$	90	[59] BRYMAN	83B	CNTR	m_{ν_x}=5 MeV
$<1.5 \times 10^{-6}$	90	BRYMAN	83B	CNTR	m_{ν_x}=53 MeV
$<1 \times 10^{-5}$	90	BRYMAN	83B	CNTR	m_{ν_x}=70 MeV
$<1 \times 10^{-4}$	90	BRYMAN	83B	CNTR	m_{ν_x}=130 MeV
$<1 \times 10^{-4}$	68	[60] SHROCK	81	THEO	m_{ν_x}=10 MeV
$<5 \times 10^{-6}$	68	[60] SHROCK	81	THEO	m_{ν_x}=60 MeV
$<1 \times 10^{-5}$	68	[61] SHROCK	80	THEO	m_{ν_x}=80 MeV
$<3 \times 10^{-6}$	68	[61] SHROCK	80	THEO	m_{ν_x}=160 MeV

[58] BRITTON 92B is from a search for additional peaks in the e^+ spectrum from $\pi^+ \to e^+ \nu_e$ decay at TRIUMF. See also BRITTON 92.
[59] BRYMAN 83B obtain upper limits from both direct peak search and analysis of B($\pi \to e\nu$)/B($\pi \to \mu\nu$). Latter limits are not listed, except for this entry (i.e. — we list the most stringent limits for given mass).
[60] Analysis of $(\pi^+ \to e^+ \nu_e)/(\pi^+ \to \mu^+ \nu_\mu)$ and $(K^+ \to e^+ \nu_e)/(K^+ \to \mu^+ \nu_\mu)$ decay ratios.
[61] Analysis of $(K^+ \to e^+ \nu_e)$ spectrum.

Kink search in nuclear β decay

High-sensitivity follow-up experiments show that indications for a neutrino with mass 17 keV (Simpson, Hime, and others) were not valid. Accordingly, we no longer list the experiments by these authors and some others which made positive claims of 17 keV neutrino emission. Complete listings are given in the 1994 edition (Physical Review **D50** 1173 (1994)) and in the 1998 edition (The European Physical Journal **C3** 1 (1998)). We list below only the best limits on $|U_{ex}|^2$ for each m_{ν_x}. See WIETFELDT 96 for a comprehensive review.

VALUE (units 10^{-3})	*CL%*	m_{ν_j} (keV)	*ISOTOPE*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<$ 4	95	14–17	^{241}Pu	Electrostatic spec	[62] DRAGOUN	99
$<$ 1	95	4–30	^{63}Ni	Mag spect	[63] HOLZSCHUH	99
10–40	90	370–640	^{37}Ar	EC ion recoil	[64] HINDI	98
$<$ 10	95	1	^{3}H	SPEC	[65] HIDDEMANN	95
$<$ 6	95	2	^{3}H	SPEC	[65] HIDDEMANN	95
$<$ 2	95	3	^{3}H	SPEC	[65] HIDDEMANN	95
$<$ 0.7	99	16.3–16.6	^{3}H	Prop chamber	[66] KALBFLEISCH	93
$<$ 2	95	13–40	^{35}S	Si(Li)	[67] MORTARA	93
$<$ 0.73	95	17	^{63}Ni	Mag spect	OHSHIMA	93
$<$ 1.0	95	10–24	^{63}Ni	Mag spect	KAWAKAMI	92
$<$ 8	90	80	^{35}S	Mag spect	[68] APALIKOV	85
$<$ 1.5	90	60	^{35}S	Mag spect	APALIKOV	85
$<$ 3.0	90	5–50		Mag spect	MARKEY	85
$<$ 0.62	90	48	^{35}S	Si(Li)	OHI	85
$<$ 0.90	90	30	^{35}S	Si(Li)	OHI	85
$<$ 4	90	140	^{64}Cu	Mag spect	[69] SCHRECK...	83
$<$ 8	90	440	^{64}Cu	Mag spect	[69] SCHRECK...	83
$<$100	90	0.1–3000		THEO	[70] SHROCK	80
$<$ 0.1	68	80		THEO	[71] SHROCK	80

[62] DRAGOUN 99 analyze the β decay spectrum of ^{241}Pu in the energy range 0.2–9.2 keV to derive limits for the admixture of heavy neutrinos. It is not competive with HOLZSCHUH 99.

[63] HOLZSCHUH 99 use an iron-free β spectrometer to measure the ^{63}Niβ decay spectrum. An analysis of the spectrum in the energy rage 33–67.8 keV is used to derive limits for the admixture of heavy neutrinos.

[64] HINDI 98 obtain a limit on heavy neutrino admixture from EC decay of ^{37}Ar by measuring the time-of-flight distribution of the recoiling ions in coincidence with x-rays or Auger electrons. The authors report upper limit for $|U_{ex}|^2$ of $\approx$ 3% for m_{ν_x}=500 keV, 1% for m_{ν_x}=550 keV, 2% for m_{ν_x}=600 keV, and 4% for m_x=650 keV. Their reported limits for $m_{\nu_x} \leq$ 450 keV are inferior to the limits of SCHRECKENBACH 83.

[65] In the beta spectrum from tritium β decay nonvanishing or mixed $m_{\overline{\nu}_1}$ state in the mass region 0.01–4 keV. For m_{ν_x} <1 keV, their upper limit on $|U_{ex}|^2$ becomes less

[66] KALBFLEISCH 93 extends the 17 keV neutrino search of BAHRAN 92, using an improved proportional chamber to which a small amount of ^{3}H is added. Systematics are significantly reduced, allowing for an improved upper limit. The authors give a 99% confidence limit on $|U_{ex}|^2$ as a function of m_{ν_x} in the range from 13.5 keV to 17.5 keV. See also the related papers BAHRAN 93, BAHRAN 93B, and BAHRAN 95 on theoretical aspects of beta spectra and fitting methods for heavy neutrinos.

[67] MORTARA 93 limit is from study using a high-resolution solid-state detector with a superconducting solenoid. The authors note that "The sensitivity to neutrino mass is verified by measurement with a mixed source of ^{35}S and ^{14}C, which artificially produces a distortion in the beta spectrum similar to that expected from the massive neutrino."
[68] This limit was taken from the figure 3 of APALIKOV 85; the text gives a more restrictive limit of 1.7×10^{-3} at CL = 90%.
[69] SCHRECKENBACH 83 is a combined measurement of the β^+ and β^- spectrum.
[70] SHROCK 80 was a retroactive analysis of data on several superallowed β decays to search for kinks in the Kurie plot.
[71] Application of test to search for kinks in β decay Kurie plots.

Searches for Decays of Massive ν

Limits on $|U_{e x}|^2$ as function of m_{ν_x}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-3}$	95	ACCIARRI	99K	L3	m_{ν_x}=80 MeV
$<5 \times 10^{-2}$	95	ACCIARRI	99K	L3	m_{ν_x}= 175 GeV
$<2 \times 10^{-5}$	95	[72] ABREU	97I	DLPH	m_{ν_x}=6 GeV
$<3 \times 10^{-5}$	95	[72] ABREU	97I	DLPH	m_{ν_x}=50 GeV
$<1.8 \times 10^{-3}$	90	[73] HAGNER	95	MWPC	m_{ν_h} = 1.5 MeV
$<2.5 \times 10^{-4}$	90	[73] HAGNER	95	MWPC	m_{ν_h} = 4 MeV
$<4.2 \times 10^{-3}$	90	[73] HAGNER	95	MWPC	m_{ν_h} = 9 MeV
$<1 \times 10^{-5}$	90	[74] BARANOV	93		m_{ν_x}=100 MeV
$<1 \times 10^{-6}$	90	[74] BARANOV	93		m_{ν_x}= 200 MeV
$<3 \times 10^{-7}$	90	[74] BARANOV	93		m_{ν_x}= 300 MeV
$<2 \times 10^{-7}$	90	[74] BARANOV	93		m_{ν_x}=400 MeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	m_{ν_x}=20 MeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	m_{ν_x}=40 MeV
all values ruled out	95	[75] BURCHAT	90	MRK2	m_{ν_x} < 19.6 GeV
$<1 \times 10^{-10}$	95	[75] BURCHAT	90	MRK2	m_{ν_x}= 22 GeV
$<1 \times 10^{-11}$	95	[75] BURCHAT	90	MRK2	m_{ν_x}= 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	m_{ν_x}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	m_{ν_x}= 42.7–45.7 GeV
$<5 \times 10^{-3}$	90	AKERLOF	88	HRS	m_{ν_x}=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF	88	HRS	m_{ν_x}=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF	88	HRS	m_{ν_x}=6 GeV
$<1.2 \times 10^{-7}$	90	BERNARDI	88	CNTR	m_{ν_x}=100 MeV
$<1 \times 10^{-8}$	90	BERNARDI	88	CNTR	m_{ν_x}=200 MeV
$<2.4 \times 10^{-9}$	90	BERNARDI	88	CNTR	m_{ν_x}=300 MeV

$<2.1 \times 10^{-9}$	90	BERNARDI	88	CNTR	m_{ν_x}=400 MeV
$<2 \times 10^{-2}$	68	[76] OBERAUER	87		m_{ν_x}=1.5 MeV
$<8 \times 10^{-4}$	68	[76] OBERAUER	87		m_{ν_x}=4.0 MeV
$<8 \times 10^{-3}$	90	BADIER	86	CNTR	m_{ν_x}=400 MeV
$<8 \times 10^{-5}$	90	BADIER	86	CNTR	m_{ν_x}=1.7 GeV
$<8 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_x}=100 MeV
$<4 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_x}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	m_{ν_x}=400 MeV
$<3 \times 10^{-5}$	90	DORENBOS...	86	CNTR	m_{ν_x}=150 MeV
$<1 \times 10^{-6}$	90	DORENBOS...	86	CNTR	m_{ν_x}=500 MeV
$<1 \times 10^{-7}$	90	DORENBOS...	86	CNTR	m_{ν_x}=1.6 GeV
$<7 \times 10^{-7}$	90	[77] COOPER-...	85	HLBC	m_{ν_x}=0.4 GeV
$<8 \times 10^{-8}$	90	[77] COOPER-...	85	HLBC	m_{ν_x}=1.5 GeV
$<1 \times 10^{-2}$	90	[78] BERGSMA	83B	CNTR	m_{ν_x}=10 MeV
$<1 \times 10^{-5}$	90	[78] BERGSMA	83B	CNTR	m_{ν_x}=110 MeV
$<6 \times 10^{-7}$	90	[78] BERGSMA	83B	CNTR	m_{ν_x}=410 MeV
$<1 \times 10^{-5}$	90	GRONAU	83		m_{ν_x}=160 MeV
$<1 \times 10^{-6}$	90	GRONAU	83		m_{ν_x}=480 MeV

[72] ABREU 97I long-lived ν_x analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.

[73] HAGNER 95 obtain limits on heavy neutrino admixture from the decay $\nu_h \rightarrow \nu_e e^+ e^-$ at a nuclear reactor for the ν_h mass range 2–9 MeV.

[74] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron. The limits are not as good as those achieved earlier by BERGSMA 83 and BERNARDI 86, BERNARDI 88.

[75] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[76] OBERAUER 87 bounds from search for $\nu \rightarrow \nu' e e$ decay mode using reactor (anti)neutrinos.

[77] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, x is not equal to 3, i.e. ν_x cannot be the dominant mass eigenstate in ν_τ since $m_{\nu_3} <$70 MeV (ALBRECHT 85I). Also, of course, x is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

[78] BERGSMA 83B also quote limits on $|U_{e3}|^2$ where the index 3 refers to the mass eigenstate dominantly coupled to the τ. Those limits were based on assumptions about the D_s mass and $D_s \rightarrow \tau \nu_\tau$ branching ratio which are no longer valid. See COOPER-SARKAR 85.

Limits on Coupling of μ to ν_x as Function of m_{ν_x}

Peak search test

Limits on B(π (or K) $\rightarrow$ $\mu\nu_x$).

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.22	90	[79] ASSAMAGAN 98	SILI	m_{ν_x} = 0.53 MeV
<0.029	90	[79] ASSAMAGAN 98	SILI	m_{ν_x} = 0.75 MeV
<0.016	90	[79] ASSAMAGAN 98	SILI	m_{ν_x} = 1.0 MeV
$<$ 4–6 $\times 10^{-5}$		[80] BRYMAN 96	CNTR	m_{ν_x} = 30–33.91 MeV
$\sim 1 \times 10^{-16}$		[81] ARMBRUSTER 95	KARM	m_{ν_x} = 33.9 MeV
$<4 \times 10^{-7}$	95	[82] BILGER 95	LEPS	$m_{\overline{\nu}_x}$ = 33.9 MeV
$<7 \times 10^{-8}$	95	[82] BILGER 95	LEPS	m_{ν_x} = 33.9 MeV
$<2.6 \times 10^{-8}$	95	[82] DAUM 95B	TOF	m_{ν_x} = 33.9 MeV
$<2 \times 10^{-2}$	90	DAUM 87		m_{ν_x}=1 MeV
$<1 \times 10^{-3}$	90	DAUM 87		m_{ν_x}=2 MeV
$<6 \times 10^{-5}$	90	DAUM 87		3 MeV $< m_{\nu_x} <$ 19.5 MeV
$<3 \times 10^{-2}$	90	[83] MINEHART 84		m_{ν_x}=2 MeV
$<1 \times 10^{-3}$	90	[83] MINEHART 84		m_{ν_x}=4 MeV
$<3 \times 10^{-4}$	90	[83] MINEHART 84		m_{ν_x}=10 GeV
$<5 \times 10^{-6}$	90	[84] HAYANO 82		m_{ν_x}=330 MeV
$<1 \times 10^{-4}$	90	[84] HAYANO 82		m_{ν_x}=70 MeV
$<9 \times 10^{-7}$	90	[84] HAYANO 82		m_{ν_x}=250 MeV
$<1 \times 10^{-1}$	90	[83] ABELA 81		m_{ν_x}=4 MeV
$<7 \times 10^{-5}$	90	[83] ABELA 81		m_{ν_x}=10.5 MeV
$<2 \times 10^{-4}$	90	[83] ABELA 81		m_{ν_x}=11.5 MeV
$<2 \times 10^{-5}$	90	[83] ABELA 81		m_{ν_x}=16–30 MeV

[79] ASSAMAGAN 98 obtain a limit on heavy neutrino admixture from π^+ decay essentially at rest, by measuring with good resolution the momentum distribution of the muons. However, the search uses an ad hoc shape correction. The authors report upper limit for $|U_{\mu x}|^2$ of 0.22 for m_ν = 0.53 MeV, 0.029 for m_ν = 0.75 MeV, and 0.016 for m_ν = 1.0 MeV at 90%CL.

[80] BRYMAN 96 search for massive unconventional neutrinos of mass m_{ν_x} in π^+ decay.

[81] ARMBRUSTER 95 study the reactions ^{12}C(ν_e,e^-) ^{12}N and ^{12}C(ν,ν') ^{12}C* induced by neutrinos from π^+ and μ^+ decay at the ISIS neutron spallation source at the Rutherford-Appleton laboratory. An anomaly in the time distribution can be interpreted as the decay $\pi^+ \rightarrow \mu^+ \nu_x$, where ν_x is a neutral weakly interacting particle with mass $\approx$ 33.9 MeV and spin 1/2. The lower limit to the branching ratio is a function of the lifetime of the new massive neutral particle, and reaches a minimum of a few $\times 10^{-16}$ for $\tau_x \sim 5$ s.

[82] From experiments of π^+ and π^- decay in flight at PSI, to check the claim of the KARMEN Collaboration quoted above (ARMBRUSTER 95).

[83] $\pi^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[84] $K^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

Peak search test

Limits on $|U_{\mu x}|^2$ as function of m_{ν_x}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1–10×10^{-4}		[85] BRYMAN	96	CNTR	m_{ν_x} = 30–33.91 MeV
$<2 \times 10^{-5}$	95	[86] ASANO	81		m_{ν_x}=70 MeV
$<3 \times 10^{-6}$	95	[86] ASANO	81		m_{ν_x}=210 MeV
$<3 \times 10^{-6}$	95	[86] ASANO	81		m_{ν_x}=230 MeV
$<6 \times 10^{-6}$	95	[87] ASANO	81		m_{ν_x}=240 MeV
$<5 \times 10^{-7}$	95	[87] ASANO	81		m_{ν_x}=280 MeV
$<6 \times 10^{-6}$	95	[87] ASANO	81		m_{ν_x}=300 MeV
$<1 \times 10^{-2}$	95	CALAPRICE	81		m_{ν_x}=7 MeV
$<3 \times 10^{-3}$	95	[88] CALAPRICE	81		m_{ν_x}=33 MeV
$<1 \times 10^{-4}$	68	[89] SHROCK	81	THEO	m_{ν_x}=13 MeV
$<3 \times 10^{-5}$	68	[89] SHROCK	81	THEO	m_{ν_x}=33 MeV
$<6 \times 10^{-3}$	68	[90] SHROCK	81	THEO	m_{ν_x}=80 MeV
$<5 \times 10^{-3}$	68	[90] SHROCK	81	THEO	m_{ν_x}=120 MeV

[85] BRYMAN 96 search for massive unconventional neutrinos of mass m_{ν_x} in π^+ decay. They interpret the result as an upper limit for the admixture of a heavy sterile or otherwise

[86] $K^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[87] Analysis of experiment on $K^+ \rightarrow \mu^+ \nu_\mu \nu_x \overline{\nu}_x$ decay.

[88] $\pi^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[89] Analysis of magnetic spectrometer experiment, bubble chamber experiment, and emulsion experiment on $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay.

[90] Analysis of magnetic spectrometer experiment on $K \rightarrow \mu, \nu_\mu$ decay.

Peak Search in Muon Capture

Limits on $|U_{\mu x}|^2$ as function of m_{ν_x}

VALUE	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<1 \times 10^{-1}$	DEUTSCH	83	m_{ν_x}=45 MeV
$<7 \times 10^{-3}$	DEUTSCH	83	m_{ν_x}=70 MeV
$<1 \times 10^{-1}$	DEUTSCH	83	m_{ν_x}=85 MeV

Searches for Decays of Massive ν

Limits on $|U_{\mu x}|^2$ as function of m_{ν_x}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5 \times 10^{-7}$	90	[91] VAITAITIS	99	CCFR	m_{ν_x}=0.28 GeV
$<8 \times 10^{-8}$	90	[91] VAITAITIS	99	CCFR	m_{ν_x}=0.37 GeV
$<5 \times 10^{-7}$	90	[91] VAITAITIS	99	CCFR	m_{ν_x}= 0.50 GeV

$<6 \times 10^{-8}$	90	[91] VAITAITIS	99	CCFR	m_{ν_x}= 1.50 GeV
$<2 \times 10^{-5}$	95	[92] ABREU	97I	DLPH	m_{ν_x}=6 GeV
$<3 \times 10^{-5}$	95	[92] ABREU	97I	DLPH	m_{ν_x}=50 GeV
$<3 \times 10^{-6}$	90	GALLAS	95	CNTR	m_{ν_x} = 1 GeV
$<3 \times 10^{-5}$	90	[93] VILAIN	95C	CHM2	m_{ν_x} = 2 GeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	m_{ν_x}=20 MeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	m_{ν_x}=40 MeV
all values ruled out	95	[94] BURCHAT	90	MRK2	m_{ν_x} < 19.6 GeV
$<1 \times 10^{-10}$	95	[94] BURCHAT	90	MRK2	m_{ν_x} = 22 GeV
$<1 \times 10^{-11}$	95	[94] BURCHAT	90	MRK2	m_{ν_x} = 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	m_{ν_x}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	m_{ν_x}= 42.7–45.7 GeV
$<5 \times 10^{-3}$	90	AKERLOF	88	HRS	m_{ν_x}=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF	88	HRS	m_{ν_x}=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF	88	HRS	m_{ν_x}=6 GeV
$<1 \times 10^{-7}$	90	BERNARDI	88	CNTR	m_{ν_x}=200 MeV
$<3 \times 10^{-9}$	90	BERNARDI	88	CNTR	m_{ν_x}=300 MeV
$<4 \times 10^{-4}$	90	[95] MISHRA	87	CNTR	m_{ν_x}=1.5 GeV
$<4 \times 10^{-3}$	90	[95] MISHRA	87	CNTR	m_{ν_x}=2.5 GeV
$<0.9 \times 10^{-2}$	90	[95] MISHRA	87	CNTR	m_{ν_x}=5 GeV
<0.1	90	[95] MISHRA	87	CNTR	m_{ν_x}=10 GeV
$<8 \times 10^{-4}$	90	BADIER	86	CNTR	m_{ν_x}=600 MeV
$<1.2 \times 10^{-5}$	90	BADIER	86	CNTR	m_{ν_x}=1.7 GeV
$<3 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_x}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	m_{ν_x}=350 MeV
$<1 \times 10^{-6}$	90	DORENBOS...	86	CNTR	m_{ν_x}=500 MeV
$<1 \times 10^{-7}$	90	DORENBOS...	86	CNTR	m_{ν_x}=1600 MeV
$<0.8 \times 10^{-5}$	90	[96] COOPER-...	85	HLBC	m_{ν_x}=0.4 GeV
$<1.0 \times 10^{-7}$	90	[96] COOPER-...	85	HLBC	m_{ν_x}=1.5 GeV

[91] VAITAITIS 99 search for $L^0_\mu \rightarrow \mu X$. See paper for rather complicated limit as function of m_{ν_x}.

[92] ABREU 97I long-lived ν_x analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.

[93] VILAIN 95C is a search for the decays of heavy isosinglet neutrinos produced by neutral current neutrino interactions. Limits were quoted for masses in the range from 0.3 to 24 GeV. The best limit is listed above.

[94] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[95] See also limits on $\left|U_{3x}\right|$ from WENDT 87.

[96] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, x is not equal to 3, i.e. ν_x cannot be the dominant mass eigenstate in ν_τ since m_{ν_3} <70 MeV (ALBRECHT 85I). Also, of course, x is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

Limits on $|U_{\tau x}|^2$ as a Function of m_{ν_x}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \times 10^{-5}$	95	[97] ABREU	97I	DLPH	m_{ν_x}=6 GeV
$<3 \times 10^{-5}$	95	[97] ABREU	97I	DLPH	m_{ν_x}=50 GeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	m_{ν_x}=20 MeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	m_{ν_x}=40 MeV
all values ruled out	95	[98] BURCHAT	90	MRK2	$m_{\nu_x} < 19.6$ GeV
$<1 \times 10^{-10}$	95	[98] BURCHAT	90	MRK2	m_{ν_x} = 22 GeV
$<1 \times 10^{-11}$	95	[98] BURCHAT	90	MRK2	m_{ν_x} = 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	m_{ν_x}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	m_{ν_x}= 42.7–45.7 GeV
$<5 \times 10^{-2}$	80	AKERLOF	88	HRS	m_{ν_x}=2.5 GeV
$<9 \times 10^{-5}$	80	AKERLOF	88	HRS	m_{ν_x}=4.5 GeV

[97] ABREU 97I long-lived ν_x analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity.

[98] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

Limits on $|U_{ax}|^2$

Where $a = e$, μ from ρ parameter in μ decay.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^{-2}$	68	SHROCK	81B	THEO	m_{ν_x}=10 GeV
$<2 \times 10^{-3}$	68	SHROCK	81B	THEO	m_{ν_x}=40 MeV
$<4 \times 10^{-2}$	68	SHROCK	81B	THEO	m_{ν_x}=70 MeV

Limits on $|U_{1j} \times U_{2j}|$ as Function of m_{ν_j}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3 \times 10^{-5}$	90	[99] BARANOV	93		m_{ν_j}= 80 MeV
$<3 \times 10^{-6}$	90	[99] BARANOV	93		m_{ν_j}= 160 MeV
$<6 \times 10^{-7}$	90	[99] BARANOV	93		m_{ν_j}= 240 MeV
$<2 \times 10^{-7}$	90	[99] BARANOV	93		m_{ν_j}= 320 MeV
$<9 \times 10^{-5}$	90	BERNARDI	86	CNTR	m_{ν_j}=25 MeV
$<3.6 \times 10^{-7}$	90	BERNARDI	86	CNTR	m_{ν_j}=100 MeV
$<3 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_j}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	m_{ν_j}=350 MeV
$<1 \times 10^{-2}$	90	BERGSMA	83B	CNTR	m_{ν_j}=10 MeV
$<1 \times 10^{-5}$	90	BERGSMA	83B	CNTR	m_{ν_j}=140 MeV
$<7 \times 10^{-7}$	90	BERGSMA	83B	CNTR	m_{ν_j}=370 MeV

[99] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron.

(E) Solar ν Experiments

SOLAR NEUTRINOS

Revised January 2000 by K. Nakamura (KEK, High Energy Accelerator Research Organization, Japan).

The Sun is a main-sequence star at a stage of stable hydrogen burning. It produces an intense flux of electron neutrinos as a consequence of nuclear fusion reactions which generate solar energy, and whose combined effect is

$$4p + 2e^- \rightarrow {}^4\mathrm{He} \ + 2\nu_e + 26.73 \ \mathrm{MeV} - E_\nu \ , \qquad (1)$$

where E_ν represents the energy taken away by neutrinos, with an average value being $\langle E_\nu \rangle \sim 0.6$ MeV. Each neutrino-producing reaction, the resulting flux, and contributions to the event rates in chlorine and gallium solar-neutrino experiments predicted by the recent Bahcall, Basu, and Pinsonneault standard solar model (SSM) calculation [1] are listed in Table 1. This SSM is regarded as the best with helium and heavy-element diffusion. Figure 1 shows the energy spectra of solar neutrinos from these reactions quoted from Ref. 1. Recently, the SSM has been shown to predict accurately the helioseismological sound velocities with a precision of 0.1% rms throughout essentially the entire Sun, greatly strengthening confidence in the solar model [1,2].

Observation of solar neutrinos directly addresses the SSM and, more generally, the theory of stellar structure and evolution which is the basis of the SSM. The Sun as a well-defined neutrino source also provides extremely important opportunities to investigate nontrivial neutrino properties such as nonzero mass and mixing, because of the wide range of matter density and the very long distance from the Sun to the Earth. In fact,

Table 1: Neutrino-producing reactions in the Sun (the first column) and their abbreviations (second column). The neutrino fluxes and event rates in chlorine and gallium solar-neutrino experiments predicted by Bahcall, Basu, and Pinsonneault [1] are listed in the third, fourth, and fifth columns respectively.

		BAHCALL 98C [1]		
Reaction	Abbr.	Flux (cm^{-2} s^{-1})	Cl (SNU*)	Ga (SNU*)
$pp \to d\,e^+\,\nu$	pp	$5.94(1.00^{+0.01}_{-0.01}) \times 10^{10}$	—	69.6
$pe^-p \to d\,\nu$	pep	$1.39(1.00^{+0.01}_{-0.01}) \times 10^{8}$	0.2	2.8
${}^3\mathrm{He}\,p \to {}^4\mathrm{He}\,e^+\nu$	hep	2.10×10^{3}	0.0	0.0
${}^7\mathrm{Be}\,e^- \to {}^7\mathrm{Li}\,\nu + (\gamma)$	^{7}Be	$4.80(1.00^{+0.09}_{-0.09}) \times 10^{9}$	1.15	34.4
${}^8\mathrm{B} \to {}^8\mathrm{Be}^*\,e^+\nu$	^{8}B	$5.15(1.00^{+0.19}_{-0.14}) \times 10^{6}$	5.9	12.4
${}^{13}\mathrm{N} \to {}^{13}\mathrm{C}\,e^+\nu$	^{13}N	$6.05(1.00^{+0.19}_{-0.13}) \times 10^{8}$	0.1	3.7
${}^{15}\mathrm{O} \to {}^{15}\mathrm{N}\,e^+\nu$	^{15}O	$5.32(1.00^{+0.22}_{-0.15}) \times 10^{8}$	0.4	6.0
${}^{17}\mathrm{F} \to {}^{17}\mathrm{O}\,e^+\nu$	^{17}F	$6.48(1.00^{+0.12}_{-0.11}) \times 10^{6}$	0.0	0.1
Total			$7.7^{+1.2}_{-1.0}$	129^{+8}_{-6}

* 1 SNU (Solar Neutrino Unit) = 10^{-36} captures per atom per second.

the currently available solar-neutrino data seem to require such neutrino properties, if one tries to understand them consistently.

So far, five solar-neutrino experiments have published results. Three of them are radiochemical experiments using ^{37}Cl (Homestake in USA) or ^{71}Ga (GALLEX at Gran Sasso in Italy and SAGE at Baksan in Russia) to capture neutrinos: ${}^{37}\mathrm{Cl}\ \nu_e \to {}^{37}\mathrm{Ar}\ e^-$ (threshold 814 keV) or ${}^{71}\mathrm{Ga}\ \nu_e \to {}^{71}\mathrm{Ge}\ e^-$ (threshold 233 keV). The produced ^{37}Ar and ^{71}Ge are both radioactive nuclei, with half lives ($\tau_{1/2}$) of 34.8 days and 11.43 days, respectively. After an exposure of the detector for two to three times $\tau_{1/2}$, the reaction products are extracted and introduced into a low-background proportional counter, and are counted for a sufficiently long period to determine the exponentially decaying

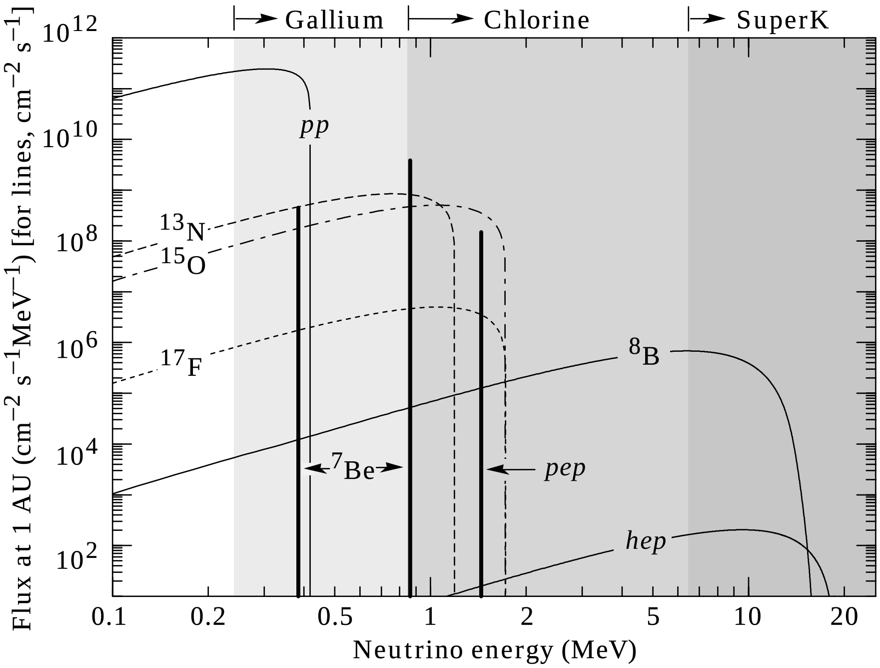


Figure 1: The solar neutrino spectrum predicted by the standard solar model. The neutrino fluxes from continuum sources are given in units of number $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{MeV}^{-1}$ at one astronomical unit, and the line fluxes are given in number $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Spectra for the *pp* chain, shown by the solid curves, are courtesy of J.N. Bahcall (1999), and reflect updates in BAHCALL 98C. Spectra for the CNO chain are shown by the dotted curves, and are courtesty of J.N. Bahcall (1995).

signal and a constant background. In the chlorine experiment, the dominant contribution comes from ^{8}B neutrinos, but ^{7}Be, *pep*, ^{13}N, and ^{15}O neutrinos also contribute. At present, the most abundant *pp* neutrinos can be detected only in gallium experiments. Even so, almost half of the capture rate in the gallium experiments is due to other solar neutrinos.

The other experiments are real-time experiments utilizing νe scattering in a large water-Čerenkov detector (Kamiokande and Super-Kamiokande in Japan). These experiments take advantage of the directional correlation between the incoming neutrino and the recoil electron. This feature greatly helps the clear separation of the solar-neutrino signal from the background. Due to the high thresholds (7 MeV in Kamiokande and 5.5 MeV at present in Super-Kamiokande) the experiments observe pure ^{8}B solar neutrinos because *hep* neutrinos contribute negligibly according to the SSM. (However, the recent Super-Kamiokande results on the recoil-electron energy spectrum at > 13 MeV raised some discussion on the possibility of an enhanced *hep* neutrino contribution [3,4].)

In May, 1999, a new realtime solar-neutrino experiment, SNO (Sudbury Neutrino Observatory) started observation. This experiment uses 1000 tons of heavy water (D_2O) to measure solar neutrinos through both inverse β decay ($\nu_e d \rightarrow e^- pp$) and neutral-current interactions ($\nu_x d \rightarrow \nu_x pn$). In addition, νe scattering events will be measured.

Solar neutrinos were first observed in the Homestake chlorine experiment in the late 1960's. From the very beginning, it was recognized that the observed capture rate was significantly smaller than the SSM prediction provided nothing happens to the electron neutrinos after they are created in the solar interior. This deficit has been called "the solar-neutrino problem."

The Kamiokande-II Collaboration started observing the ^{8}B solar neutrinos at the beginning of 1987. Because of the strong directional correlation of νe scattering, this result gave the first direct evidence that the Sun emits neutrinos (no directional information is available in radiochemical solar-neutrino experiments.) The observed solar-neutrino flux was also significantly less than the SSM prediction. In addition, Kamiokande-II obtained the energy spectrum of recoil electrons and the fluxes separately measured in the daytime and nighttime. The Kamiokande-II experiment came to an end at the beginning of 1995.

GALLEX presented the first evidence of *pp* solar-neutrino observation in 1992. Here also, the observed capture rate is significantly less than the SSM prediction. SAGE, after the initial confusion which is ascribed to statistics by the group, observed a similar capture rate to that of GALLEX. Both GALLEX and SAGE groups tested the overall detector response with intense man-made ^{51}Cr neutrino sources, and observed good agreement between the measured ^{71}Ge production rate and that predicted from the source activity, demonstrating the reliability of these experiments. The GALLEX Collaboration formally finished observations in early 1997. Since April, 1998, a newly defined collaboration, GNO (Gallium Neutrino Observatory) resumed the observations.

Super-Kamiokande is a 50-kton second-generation solar-neutrino detector, which is characterized by a significantly larger counting rate than the first-generation experiments. This experiment started observation in April 1996. The average solar-neutrino flux is smaller than, but consistent with, the Kamiokande-II result. However, the flux measured in the nighttime shows an excess over that measured in the daytime [5,6], though the significance is not yet high. Super-Kamiokande also observed the recoil-electron energy spectrum [7]. Its shape showed an excess at the high-energy end ($>$ 13 MeV) compared to the SSM expectation, though its statistical significance is not very high. More recent results indicate that the high-energy excess is reduced with the accumulation of statistics.

The most recent published results on the average capture rates or flux from solar-neutrino experiments are listed in Table 2 and compared to the results from SSM calculations which are taken from "Lepton Particle Listings (E) Solar ν Experiments" in this edition of "Review of Particle Physics." In these calculations, BAHCALL 98C [1], BRUN 98 [12], BAHCALL 95B [14], and DAR 96 [13] take into account helium and heavy-element diffusion, but other calculations do not. SSM calculations give essentially the same results for the same input parameters and physics. This statement applies to the most recent BAHCALL 98C [1] and BRUN 98 [12] models. The BAHCALL 98C model [1] differs from the BAHCALL 95B model [14] in that BAHCALL 98C [1] uses the nuclear fusion rates systematically reevaluated and recommended by Adelberger *et al.* [24], and other best available input data. The ^{7}Be$(p,\gamma)^8$B cross section adopted by Adelberger *et al.* [24] is 15% lower than the value used by BAHCALL 95B [14]. This is the principal reason why the ^{8}B neutrino flux and the ^{37}Cl and ^{71}Ga capture rates calculated by the BAHCALL 98C model [1] are lower than those calculated by the BAHCALL 95B model [14]. The BAHCALL 95B [14] model and the TURCK-CHIEZE 93B [15] model differ primarily in that BAHCALL 95B [14] includes element diffusion. The DAR 96 [13] model differs significantly from the BAHCALL 95B [14] model mostly due to the use of nonstandard reaction rates, different treatments of diffusion, and the equation of state.

All results from the present solar-neutrino experiments indicate significantly less flux than expected from SSM calculations except those of DAR 96 [13]. The DAR 96 [13] model predicts the ^{8}B solar-neutrino flux which is consistent with the Kamiokande-II and Super-Kamiokande results, but even this

Table 2: Recent results from the five solar-neutrino experiments and a comparison with theoretical solar-model predictions. Solar model calculations are also presented. The evolution of these results over the years gives some feeling for their robustness as the models have become more sophisticated and complete.

	^{37}Cl→^{37}Ar (SNU)	^{71}Ga→^{71}Ge (SNU)	^{8}B ν flux (10^6cm^{-2}s^{-1})
Homestake			
(CLEVELAND 98)[8]	$2.56 \pm 0.16 \pm 0.16$	—	—
GALLEX			
(HAMPEL 99)[9]	—	$77.5 \pm 6.2^{+4.3}_{-4.7}$	—
SAGE			
(ABDURASHI...99B)[10]	—	$67.2^{+7.2+3.5}_{-7.0-3.0}$	—
Kamiokande			
(FUKUKDA 96)[11]	—	—	$2.80 \pm 0.19 \pm 0.33$
Super-Kamiokande			
(FUKUKDA 99)[5]	—	—	$2.436^{+0.053+0.085}_{-0.047-0.071}$
(BAHCALL 98C)[1]	$7.7^{+1.2}_{-1.0}$	129^{+8}_{-6}	$5.15(1.00^{+0.19}_{-0.14})$
(BRUN 98)[12]	7.18	127.2	4.82
(DAR 96)[13]	4.1 ± 1.2	115 ± 6	2.49
(BAHCALL 95B)[14]	$9.3^{+1.2}_{-1.4}$	137^{+8}_{-7}	$6.6(1.00^{+0.14}_{-0.17})$
(TURCK-CHIEZE 93B)[15]	6.4 ± 1.4	123 ± 7	4.4 ± 1.1
(BAHCALL 92)[16]	$8.0 \pm 3.0^{\dagger}$	$132^{+21\dagger}_{-17}$	$5.69(1.00 \pm 0.43)^{\dagger}$
(BAHCALL 88)[17]	$7.9 \pm 2.6^{\dagger}$	$132^{+20\dagger}_{-17}$	$5.8(1.00 \pm 0.37)^{\dagger}$
(TURCK-CHIEZE 88)[18]	5.8 ± 1.3	125 ± 5	$3.8(1.00 \pm 0.29)$
(FILIPPONE 83)[19]	5.6	—	—
(BAHCALL 82)[20]	$7.6 \pm 3.3^{\dagger}$	$106^{+13\dagger}_{-8}$	5.6
(FILIPPONE 82)[21]	7.0 ± 3.0	111 ± 13	4.8
(FOWLER 82)[22]	6.9 ± 1.0	—	—
(BAHCALL 80)[23]	7.3	—	—

* 1 SNU (Solar Neutrino Unit) = 10^{-36} captures per atom per second.

† "3σ" errors.

model predicts ^{37}Cl and ^{71}Ga capture rates significantly larger than the Homestake, GALLEX, and SAGE results.

Is there any possible consistent explanation of all the results of solar-neutrino observations in the framework of the standard solar model? This is difficult because the Homestake result and the Kamiokande result, taken at face value, are mutually inconsistent if one assumes standard neutrino spectra. That is, with the reduction factor of the ^{8}B solar-neutrino flux as determined from the Kamiokande result, the Homestake ^{37}Cl capture rate would be oversaturated, and there would be no room to accommodate the ^{7}Be solar neutrinos. This makes astrophysical solutions untenable because ^{8}B nuclei are produced from ^{7}Be nuclei in the Sun.

Several authors made more elaborate analyses using the constraint of observed solar luminosity, and found (see for example, Refs. 25–28)

- that both the comparison of the Kamiokande and gallium results and the comparison of the gallium and chlorine results also indicate strong suppression of the ^{7}Be solar-neutrino flux, and
- that not only the SSM but also nonstandard solar models are incompatible with the observed data.

In view of the above situation, it is attractive to invoke nontrivial neutrino properties. Neutrino oscillation in matter (MSW mechanism) is particularly attractive in explaining all the experimental data on the average solar-neutrino flux consistently, without any *a priori* assumptions or fine tuning. Several authors made extensive MSW analyses using all the available data and ended up with similar results. For example, Bahcall, Krastev, and Smirnov [28] analyzed the solar-neutrino data as of 1998 in terms of two-flavor oscillations. In addition, they analyzed the case of vacuum oscillations. They obtained the following solutions for the BAHCALL 98C [1] SSM: Using only the total event rates in the five solar-neutrino experiments, there are three MSW solutions and one vacuum-oscillation solution at the 99% confidence level for oscillations into active neutrinos (ν_μ or ν_τ).

- Small mixing-angle (SMA) solution:
  $\Delta m^2 = 5.4 \times 10^{-6}$ eV^2, $\sin^2 2\theta = 6.0 \times 10^{-3}$
- Large mixing-angle (LMA) solution:
  $\Delta m^2 = 1.8 \times 10^{-5}$ eV^2, $\sin^2 2\theta = 0.76$
- LOW (low probability or low mass) solution:
  $\Delta m^2 = 7.9 \times 10^{-8}$ eV^2, $\sin^2 2\theta = 0.96$
- Vacuum (VAC) solution:
  $\Delta m^2 = 8.0 \times 10^{-11}$ eV^2, $\sin^2 2\theta = 0.75$.

In the case of oscillations into sterile neutrinos, only the SMA and VAC solutions are allowed at the 99% confidence level with the best-fit parameters similar to the ones given above.

Bahcall, Krastev, and Smirnov [28] also made global analyses using all of the available solar-neutrino data, *i.e.*, total event rates plus the Super-Kamiokande recoil-electron energy spectrum and day-night asymmetry. At the 99% confidence level, acceptable solutions are found to be SMA (oscillations into both active and sterile neutrinos) and VAC. The LMA and LOW solutions are marginally ruled out.

Assuming that the solution to the solar-neutrino problem will really be provided by neutrino oscillations, how can one discriminate various solutions? The MSW SMA solution causes an energy-spectrum distortion. In the Super-Kamiokande and SNO observations, the flux will be more suppressed at lower energies. The MSW LMA solution predicts the day-night flux difference, a hint of which is seen in the recent Super-Kamiokande results [6]. However, the LMA solution gives almost no spectrum distortion. Thus, should LMA be a correct solution, one needs to explain the high-energy excess in the recoil-electron spectrum observed by Super-Kamiokande [7], if it turns out to be a real effect, due to a very large contribution from *hep* neutrinos or from other possibilities [4]. The VAC solution is characterized by seasonal variation of the flux, which is different from the trivial variation due to the eccentricity of Earth's orbit [29,30]. Also, the VAC solution can explain the high-energy excess of the recoil-electron spectrum observed by Super-Kamiokande [30].

SNO's observations of solar-neutrino flux by neutral-current reactions will give decisive evidence for neutrino oscillations into active neutrinos, if that flux is consistent with the SSM prediction and larger than the flux measured by charged-current reactions. On the other hand, the signal for oscillations into sterile neutrinos will be the same amount of reduction of the fluxes measured by neutral- and charged-current reactions.

An important task of the second-generation solar neutrino experiments is the measurement of monochromatic ^{7}Be solar neutrinos. If the VAC solution is correct, the flux of ^{7}Be neutrinos shows larger seasonal variations than the flux of ^{8}B neutrinos. The ^{7}Be neutrino flux will be measured by a new experiment, Borexino, at Gran Sasso *via* νe scattering in 300 tons of ultra-pure liquid scintillator with a detection threshold as low as 250 keV. The Borexino detector is expected to be completed in 2001.

KamLAND, which is under construction at Kamioka and will be completed in 2001, is a multi-purpose neutrino experiment with 1000 tons of ultra-pure liquid scintillator. This experiment will also observe ^{7}Be neutrinos if the detection threshold can be lowered to a level similar to that of Borexino. However, one of the primary purposes of this experiment is the observation of oscillations of neutrinos produced by power reactors. The sensitivity region of KamLAND includes the MSW LMA solution. Thus, the LMA solution may be proved or excluded by KamLAND.

The second-generation solar-neutrino experiments, Super-Kamiokande, SNO, and Borexino, as well as KamLAND, will provide a variety of data with high statistical accuracy. It is hoped that these experiments will solve the long-standing solar-neutrino problem in coming years.

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1 SNU (Solar Neutrino Unit) = 10^{-36} captures per atom per second.

VALUE	DOCUMENT ID		TECN	COMMENT
$67.2^{+7.2}_{-7.0}{}^{+3.5}_{-3.0}$ SNU	[100] ABDURASHI...	99B	SAGE	$^{71}\text{Ga} \rightarrow {}^{71}\text{Ge}$
$(2.44 \pm 0.05^{+0.09}_{-0.07}) \times 10^6$ cm^{-2}s^{-1}	[101] FUKUDA	99	SKAM	^{8}B ν flux (all)
$(2.37 \pm 0.07) \times 10^6$ cm^{-2}s^{-1}	[101] FUKUDA	99	SKAM	^{8}B ν flux (day)
$(2.48^{+0.07}_{-0.06}) \times 10^6$ cm^{-2}s^{-1}	[101] FUKUDA	99	SKAM	^{8}B ν flux (night)
	[102] FUKUDA	99B	SKAM	Recoil e spectrum
$77.5 \pm 6.2^{+4.3}_{-4.7}$ SNU	[103] HAMPEL	99	GALX	$^{71}\text{Ga} \rightarrow {}^{71}\text{Ge}$
$2.56 \pm 0.16 \pm 0.16$ SNU	[104] CLEVELAND	98	HOME	^{37}Cl radiochem.
$(2.80 \pm 0.19 \pm 0.33) \times 10^6$cm^{-2}s^{-1}	[105] FUKUDA	96	KAMI	^{8}Bν flux
$(2.70 \pm 0.27) \times 10^6$cm^{-2}s^{-1}	[105] FUKUDA	96	KAMI	^{8}Bν flux (day)
$(2.87^{+0.27}_{-0.26}) \times 10^6$cm^{-2}s^{-1}	[105] FUKUDA	96	KAMI	^{8}Bν flux (night)

[100] ABDURASHITOV 99B is a detailed report of the SAGE solar-neutrino experiment during the period January 1990 through December 1997, and updates the ABDURASHITOV 94 result. However the data in the period November 1993 through June 1994 were not used in determining the neutrino capture rate due to some uncertainty with respect to experimental control. A total of 211 ^{71}Ge events were observed.

[101] FUKUDA 99 results are for a total of 503.8 live days with Super-Kamiokande between 31 May 1996 and 25 March 1998, with threshold $E_e > 6.5$ MeV, and replace FUKUDA 98B results. The day-night solar-neutrino flux asymmetry is given as N/D$-$1=$0.047 \pm 0.042 \pm 0.008$. The results are also given for night fluxes subdivided into five data sets according to nadir of the Sun at the time of the neutrino event. FUKUDA 99 set an absolute flux-independent exclusion region in the two-neutrino oscillation parameter space from the absence of a significant day-night variation. Except for $+0.6\%/-0.5\%$, the systematic errors are common to day and night fluxes.

[102] FUKUDA 99B reports the energy spectrum of recoil electrons from elastic scattering of solar neutrinos for a total of 503.8 live days of Super-Kamiokande observation. A comparison of the observed spectrum with the expectation is in poor agreement at the 4.6% confidence level.

[103] HAMPEL 99 report the combined result for GALLEX I+II+III+IV (65 runs in total), which update the HAMPEL 96 result. The GALLEX IV result (12 runs) is $118.4 \pm 17.8 \pm 6.6$ SNU. (HAMPEL 99 discuss the consistency of partial results with the mean.) The GALLEX experimental program has been completed with these runs. The total run data cover the period 14 May 1991 through 23 January 1997. A total of 300 ^{71}Ge events were observed.

[104] CLEVELAND 98 is a detailed report of the ^{37}Cl experiment at the Homestake Mine. The average solar neutrino-induced ^{37}Ar production rate from 108 runs between 1970 and 1994 updates the DAVIS 89 result.

[105] FUKUDA 96 results are for a total of 2079 live days with Kamiokande II and III from January 1987 through February 1995, covering the entire solar cycle 22, with threshold $E_e > 9.3$ MeV (first 449 days), > 7.5 MeV (middle 794 days), and > 7.0 MeV (last 836 days). These results update the HIRATA 90 result for the average ^{8}B solar-neutrino flux and HIRATA 91 result for the day-night variation in the ^{8}B solar-neutrino flux. The total data sample was also analyzed for short-term variations: within experimental errors, no strong correlation of the solar-neutrino flux with the sunspot numbers was found.

(F) Astrophysical neutrino observations

Neutrinos and antineutrinos produced in the atmosphere induce μ-like and e-like events in underground detectors. The ratio of the numbers of the two kinds of events is defined as μ/e. It has the advantage that systematic effects, such as flux uncertainty, tend to cancel, for both experimental and theoretical values of the ratio. The "ratio of the ratios" of experimental to theoretical μ/e, $R(\mu/e)$, or that of experimental to theoretical μ/total, $R(\mu/\text{total})$ with total $= \mu+e$, is reported below. If the actual value is not unity, the value obtained in a given experiment may depend on the experimental conditions.

R(μ/e) = (Measured Ratio μ/e) / (Expected Ratio μ/e)

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.64 \pm 0.11 \pm 0.06$	[106] ALLISON	99	SOU2	Calorimeter
$0.61 \pm 0.03 \pm 0.05$	[107] FUKUDA	98	SKAM	sub-GeV
$0.66 \pm 0.06 \pm 0.08$	[108] FUKUDA	98E	SKAM	multi-GeV
	[109] FUKUDA	96B	KAMI	Water Cerenkov
$1.00 \pm 0.15 \pm 0.08$	[110] DAUM	95	FREJ	Calorimeter
$0.60^{+0.06}_{-0.05} \pm 0.05$	[111] FUKUDA	94	KAMI	sub-GeV
$0.57^{+0.08}_{-0.07} \pm 0.07$	[112] FUKUDA	94	KAMI	multi-Gev
	[113] BECKER-SZ...	92B	IMB	Water Cerenkov

[106] ALLISON 99 result is based on an exposure of 3.9 kton yr, 2.6 times the exposure reported in ALLISON 97, and replaces that result.

[107] FUKUDA 98 result is based on an exposure of 25.5 kton yr. The analyzed data sample consists of fully-contained e-like events with 0.1 GeV/$c < p_e$ and μ-like events with 0.2 GeV/$c < p_\mu$, both having a visible energy $<$ 1.33 GeV. These criteria match the definition used by FUKUDA 94.

[108] FUKUDA 98E result is based on an exposure of 25.5 kton yr. The analyzed data sample consists of fully-contained single-ring events with visible energy $>$ 1.33 GeV and partially contained events. All partially contained events are classified as μ-like.

[109] FUKUDA 96B studied neutron background in the atmospheric neutrino sample observed in the Kamiokande detector. No evidence for the background contamination was found.

[110] DAUM 95 results are based on an exposure of 2.0 kton yr which includes the data used by BERGER 90B. This ratio is for the contained and semicontained events. DAUM 95 also report $R(\mu/e) = 0.99 \pm 0.13 \pm 0.08$ for the total neutrino induced data sample which includes upward going stopping muons and horizontal muons in addition to the contained and semicontained events.

[111] FUKUDA 94 result is based on an exposure of 7.7 kton yr and updates the HIRATA 92 result. The analyzed data sample consists of fully-contained e-like events with $0.1 < p_e < 1.33$ GeV/c and fully-contained μ-like events with $0.2 < p_\mu < 1.5$ GeV/c.

[112] FUKUDA 94 analyzed the data sample consisting of fully contained events with visible energy $>$ 1.33 GeV and partially contained μ-like events.

[113] BECKER-SZENDY 92B reports the fraction of nonshowering events (mostly muons from atomospheric neutrinos) as $0.36 \pm 0.02 \pm 0.02$, as compared with expected fraction $0.51 \pm 0.01 \pm 0.05$. After cutting the energy range to the Kamiokande limits, BEIER 92 finds $R(\mu/e)$ very close to the Kamiokande value.

R(ν_μ) = (Measured Flux of ν_μ) / (Expected Flux of ν_μ)

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.74 \pm 0.036 \pm 0.046$	[114] AMBROSIO	98	MCRO	Streamer tubes
	[115] CASPER	91	IMB	Water Cherenkov
	[116] AGLIETTA	89	NUSX	
0.95 ± 0.22	[117] BOLIEV	81		Baksan
0.62 ± 0.17	CROUCH	78		Case Western/UCI

[114] AMBROSIO 98 result is for all nadir angles and updates AHLEN 95 result. The lower cutoff on the muon energy is 1 GeV. In addition to the statistical and systematic errors, there is a Monte Carlo flux error (theoretical error) of ± 0.13. With a neutrino oscillation hypothesis, the fit either to the flux or zenith distribution independently yields $\sin^2 2\theta = 1.0$ and $\Delta(m^2) \sim$ a few times 10^{-3} eV^2. However, the fit to the observed zenith distribution gives a maximum probability for χ^2 of only 5% for the best oscillation hypothesis.

[115] CASPER 91 correlates showering/nonshowering signature of single-ring events with parent atmospheric-neutrino flavor. They find nonshowering ($\approx \nu_\mu$ induced) fraction is $0.41 \pm 0.03 \pm 0.02$, as compared with expected 0.51 ± 0.05 (syst).

[116] AGLIETTA 89 finds no evidence for any anomaly in the neutrino flux. They define ρ = (measured number of ν_e's)/(measured number of ν_μ's). They report $\rho(\text{measured}) = \rho(\text{expected}) = 0.96^{+0.32}_{-0.28}$.

[117] From this data BOLIEV 81 obtain the limit $\Delta(m^2) \leq 6 \times 10^{-3}$ eV^2 for maximal mixing, $\nu_\mu \not\to \nu_\mu$ type oscillation.

R(μ/total) = (Measured Ratio μ/total) / (Expected Ratio μ/total)

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.1^{+0.07}_{-0.12} \pm 0.11$	[118] CLARK	97	IMB	multi-GeV

[118] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cerenkov detector with visible energy > 0.95 GeV.

$N_{\text{up}}(\mu)/N_{\text{down}}(\mu)$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.52^{+0.07}_{-0.06} \pm 0.01$	[119] FUKUDA	98E	SKAM	multi-GeV

[119] FUKUDA 98E result is based on an exposure of 25.5 kton yr. The analyzed data sample consists of fully-contained single-ring μ-like events with visible energy > 1.33 GeV and partially contained events. All partially contained events are classified as μ-like. Upward-going events are those with $-1 <$ cos (zenith angle) < -0.2 and downward-going events with those with $0.2 <$ cos (zenith angle) < 1. FUKUDA 98E result strongly deviates from an expected value of $0.98 \pm 0.03 \pm 0.02$.

$N_{up}(e)/N_{down}(e)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.84^{+0.14}_{-0.12}\pm0.02$	[120] FUKUDA	98E	SKAM	multi-GeV

[120] FUKUDA 98E result is based on an exposure of 25.5 kton yr. The analyzed data sample consists of fully-contained single-ring e-like events with visible energy $>$ 1.33 GeV. Upward-going events are those with $-1 <$cos (zenith angle) < -0.2 and downward-going events are those with 0.2 $<$cos (zenith angle) $<$ 1. FUKUDA 98E result is conpared to an expected value of 1.01 $\pm$ 0.06 $\pm$ 0.03.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ $(\nu_e \leftrightarrow \nu_\mu)$

For a review see BAHCALL 89.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$0.6	90	[121] OYAMA	98	KAMI	$\Delta(m^2) > 0.1$ eV^2
$<$0.5		[122] CLARK	97	IMB	$\Delta(m^2) > 0.1$ eV^2
$>$0.55	90	[123] FUKUDA	94	KAMI	$\Delta(m^2) =$ 0.007–0.08 eV^2
$<$0.47	90	[124] BERGER	90B	FREJ	$\Delta(m^2) > 1$ eV^2
$<$0.14	90	LOSECCO	87	IMB	$\Delta(m^2)=$ 0.00011 eV^2

[121] OYAMA 98 obtained this result by an analysis of upward-going muons in Kamiokande. The data sample used is essentially the same as that used by HATAKEYAMA 98.

[122] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cerenkov detector with visible energy $>$ 0.95 GeV.

[123] FUKUDA 94 obtained this result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande.

[124] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ $(\nu_e \leftrightarrow \nu_\mu)$

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<$560	90	[125] OYAMA	98	KAMI
$<$980		[126] CLARK	97	IMB
$700 < \Delta(m^2) < 7000$	90	[127] FUKUDA	94	KAMI
$<$150	90	[128] BERGER	90B	FREJ

[125] OYAMA 98 obtained this result by an analysis of upward-going muons in Kamiokande. The data sample used is essentially the same as that used by HATAKEYAMA 98.

[126] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cerenkov detector with visible energy $>$ 0.95 GeV.

[127] FUKUDA 94 obtained this result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande.

[128] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\overline{\nu}_e \leftrightarrow \overline{\nu}_\mu$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.9	99	[129] SMIRNOV	94	THEO	$\Delta(m^2) > 3 \times 10^{-4}$ eV^2
<0.7	99	[129] SMIRNOV	94	THEO	$\Delta(m^2) < 10^{-11}$ eV^2

[129] SMIRNOV 94 analyzed the data from SN 1987A using stellar-collapse models. They also give less stringent upper limits on $\sin^2 2\theta$ for $10^{-11} < \Delta(m^2) < 3 \times 10^{-7}$ eV^2 and $10^{-5} < \Delta(m^2) < 3 \times 10^{-4}$ eV^2. The same results apply to $\overline{\nu}_e \leftrightarrow \overline{\nu}_\tau$, ν_μ, and ν_τ.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.4	90	[130] FUKUDA	99C	SKAM	$\Delta(m^2)$= 0.001–0.1 eV^2
>0.7	90	[131] FUKUDA	99D	SKAM	$\Delta(m^2)$= 0.0015–0.015 eV^2
>0.82	90	[132] AMBROSIO	98	MCRO	$\Delta(m^2) \sim 0.0025$ eV^2
>0.82	90	[133] FUKUDA	98C	SKAM	$\Delta(m^2)$ = 0.0005–0.006 eV^2
>0.3	90	[134] HATAKEYAMA	98	KAMI	$\Delta(m^2)$= 0.00055–0.14 eV^2
>0.73	90	[135] HATAKEYAMA	98	KAMI	$\Delta(m^2)$= 0.004–0.025 eV^2
<0.7		[136] CLARK	97	IMB	$\Delta(m^2) >$ 0.1 eV^2
>0.65	90	[137] FUKUDA	94	KAMI	$\Delta(m^2)$ = 0.005–0.03 eV^2
<0.5	90	[138] BECKER-SZ...	92	IMB	$\Delta(m^2)$= 1–2 $\times 10^{-4}$ eV^2
<0.6	90	[139] BERGER	90B	FREJ	$\Delta(m^2) > 1$ eV^2

[130] FUKUDA 99C obtained this result from a total of 537 live days of upward through-going muon data in Super-Kamiokande between April 1996 to January 1998. With a threshold of $E_\mu > 1.6$ GeV, the observed flux of upward through-going muons is $(1.74 \pm 0.07 \pm 0.02) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. The zenith-angle dependence of the flux does not agree with no-oscillation predictions. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, FUKUDA 99C obtained the best fit at $\sin^2 2\theta$=0.95 and $\Delta(m^2)$=5.9×10^{-3} eV^2. FUKUDA 99C also reports 68% and 99% confidence-level allowed regions for the same hypotheis.

[131] FUKUDA 99D obtained this result from a simultaneous fitting to zenith angle distributions of upward-stopping and through-going muons. The flux of upward-stopping muons of minimum energy of 1.6 GeV measured between April 1996 and January 1998 is $(0.39 \pm 0.04 \pm 0.02) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. This is compared to the expected flux of $(0.73 \pm 0.16$ (theoretical error)$) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. The flux of upward through-going muons is taken from FUKUDA 99C. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, FUKUDA 99D obtained the best fit in the physical region at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.9×10^{-3} eV^2. FUKUDA 99D also reports 68% and 99% confidence-level allowed regions for the same hypothesis. FUKUDA 99D further reports the result of the oscillation analysis using the zenith-angle dependence of upward-stopping/through-going flux ratio. The best fit in the physical region is obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.1×10^{-3} eV^2.

[132] AMBROSIO 98 result is only 17% probable at maximum because of relatively low flux for $\cos\theta < -0.8$.

[133] FUKUDA 98C obtained this result by an analysis of 33.0 kton yr atmospheric-neutrino data which include the 25.5 kton yr data used by FUKUDA 98 (sub-GeV) and FUKUDA 98E (multi-GeV). Inside the physical region, the best fit was obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=2.2×10^{-3} eV^2. In addition, FUKUDA 98C gave the 99% confidence interval, $\sin^2 2\theta > 0.73$ and $3 \times 10^{-4} < \Delta(m^2) < 8.5 \times 10^{-3}$ eV^2. FUKUDA 98C also tested the $\nu_\mu \rightarrow \nu_e$ hypothesis, and concluded that it is not favored.

[134] HATAKEYAMA 98 obtained this result from a total of 2456 live days of upward-going muon data in Kamiokande between December 1985 and May 1995. With a threshold of $E_\mu > 1.6$ GeV, the observed flux of upward through-going muon is $(1.94 \pm 0.10^{+0.07}_{-0.06}) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. This is compared to the expected flux of (2.46 ± 0.54 (theoretical error)) $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, the best fit inside the physical region was obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.2 $\times 10^{-3}$ eV^2.

[135] HATAKEYAMA 98 obtained this result from a combined analysis of Kamiokande's contained events (FUKUDA 94) and upward-going muon events. The best fit was obtained at $\sin^2 2\theta$=0.95 and $\Delta(m^2)$=1.3 $\times 10^{-2}$ eV^2.

[136] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cerenkov detector with visible energy > 0.95 GeV.

[137] FUKUDA 94 obtained this result by a combined analysis of sub-and multi-GeV atmospheric neutrino events in Kamiokande.

[138] BECKER-SZENDY 92 uses upward-going muons to search for atmospheric ν_μ oscillations. The fraction of muons which stop in the detector is used to search for deviations in the expected spectrum. No evidence for oscillations is found.

[139] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
100< $\Delta(m^2)$ < 5000	90	[140] FUKUDA	99C	SKAM
150< $\Delta(m^2)$ < 1500	90	[141] FUKUDA	99D	SKAM
50< $\Delta(m^2)$ < 600	90	[142] AMBROSIO	98	MCRO
50< $\Delta(m^2)$ < 600	90	[143] FUKUDA	98C	SKAM
55< $\Delta(m^2)$ < 5000	90	[144] HATAKEYAMA	98	KAMI
400< $\Delta(m^2)$ < 2300	90	[145] HATAKEYAMA	98	KAMI
<1500		[146] CLARK	97	IMB
500 < $\Delta(m^2)$ < 2500	90	[147] FUKUDA	94	KAMI
< 350	90	[148] BERGER	90B	FREJ

[140] FUKUDA 99C obtained this result from a total of 537 live days of upward through-going muon data in Super-Kamiokande between April 1996 to January 1998. With a threshold of $E_\mu > 1.6$ GeV, the observed flux of upward through-going muon is (1.74 ± 0.07 ± 0.02) $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. The zenith-angle dependence of the flux does not agree with no-oscillation predictions. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, FUKUDA 99C obtained the best fit at $\sin^2 2\theta$=0.95 and $\Delta(m^2)$=5.9 $\times 10^{-3}$ eV^2. FUKUDA 99C also reports 68% and 99% confidence-level allowed regions for the same hypotheis.

[141] FUKUDA 99D obtained this result from a simultaneous fitting to zenith angle distributions of upward-stopping and through-going muons. The flux of upward-stopping muons of minimum energy of 1.6 GeV measured between April 1996 and January 1998 is (0.39 ± 0.04 ± 0.02) $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. This is compared to the expected flux of (0.73 ± 0.16 (theoretical error)) $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. The flux of upward through-going muons is taken from FUKUDA 99C. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, FUKUDA 99D obtained the best fit in the physical region at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.9 $\times 10^{-3}$ eV^2. FUKUDA 99D also reports 68% and 99% confidence-level allowed regions for the same hypothesis. FUKUDA 99D further reports the result of the oscillation analysis using the zenith-angle dependence of upward-stopping/through-going flux ratio. The best fit in the physical region is obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.1 $\times 10^{-3}$ eV^2.

[142] AMBROSIO 98 result is only 17% probable at maximum because of relatively low flux for $\cos\theta < -0.8$.

[143] FUKUDA 98C obtained this result by an analysis of 33.0 kton yr atmospheric-neutrino data which include the 25.5 kton yr data used by FUKUDA 98 (sub-GeV) and FUKUDA 98E (multi-GeV). Inside the physical region, the best fit was obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=2.2×10^{-3} eV^2. In addition, FUKUDA 98C gave the 99% confidence interval, $\sin^2 2\theta > 0.73$ and $3\times10^{-4} < \Delta(m^2) < 8.5\times10^{-3}$ eV^2. FUKUDA 98C also tested the $\nu_\mu \rightarrow \nu_e$ hypothesis, and concluded that it is not favored.

[144] HATAKEYAMA 98 obtained this result from a total of 2456 live days of upward-going muon data in Kamiokande between December 1985 and May 1995. With a threshold of $E_\mu > 1.6$ GeV, the observed flux of upward through-going muon is $(1.94 \pm 0.10^{+0.07}_{-0.06}) \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. This is compared to the expected flux of (2.46 ± 0.54 (theoretical error)) $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, the best fit inside the physical region was obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.2×10^{-3} eV^2.

[145] HATAKEYAMA 98 obtained this result from a combined analysis of Kamiokande's contained events (FUKUDA 94) and upward-going muon events. The best fit was obtained at $\sin^2 2\theta$=0.95 and $\Delta(m^2)$=1.3×10^{-2} eV^2.

[146] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cerenkov detector with visible energy > 0.95 GeV.

[147] FUKUDA 94 obtained this result by a combined analysis of sub-and multi-GeV atmospheric neutrino events in Kamiokande.

[148] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \rightarrow \nu_s$)

ν_s means ν_τ or any sterile (noninteracting) ν.

VALUE (10^{-5} eV^2)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3000 (or <550)	90	[149] OYAMA	89	KAMI	Water Cerenkov
< 4.2 or > 54.	90	BIONTA	88	IMB	Flux has ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$

[149] OYAMA 89 gives a range of limits, depending on assumptions in their analysis. They argue that the region $\Delta(m^2)$ = (100–1000) $\times 10^{-5}$ eV^2 is not ruled out by any data for large mixing.

(G) Reactor $\overline{\nu}_e$ disappearance experiments

In most cases, the reaction $\overline{\nu}_e p \rightarrow e^+ n$ is observed at different distances from one or more reactors in a complex.

Events (Observed/Expected) from Reactor $\overline{\nu}_e$ Experiments

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.01 \pm 0.028 \pm 0.027$	[150] APOLLONIO	99	CHOZ	Chooz reactors 1 km
$0.987 \pm 0.006 \pm 0.037$	[151] GREENWOOD	96		Savannah River, 18.2 m
$0.988 \pm 0.004 \pm 0.05$	ACHKAR	95	CNTR	Bugey reactor, 15 m
$0.994 \pm 0.010 \pm 0.05$	ACHKAR	95	CNTR	Bugey reactor, 40 m
$0.915 \pm 0.132 \pm 0.05$	ACHKAR	95	CNTR	Bugey reactor, 95 m
$0.987 \pm 0.014 \pm 0.027$	[152] DECLAIS	94	CNTR	Bugey reactor, 15 m
$0.985 \pm 0.018 \pm 0.034$	KUVSHINN...	91	CNTR	Rovno reactor
$1.05 \pm 0.02 \pm 0.05$	VUILLEUMIER	82		Gösgen reactor
$0.955 \pm 0.035 \pm 0.110$	[153] KWON	81		$\overline{\nu}_e p \rightarrow e^+ n$
0.89 ± 0.15	[153] BOEHM	80		$\overline{\nu}_e p \rightarrow e^+ n$
0.38 ± 0.21	[154,155] REINES	80		
0.40 ± 0.22	[154,155] REINES	80		

[150] APOLLONIO 99, APOLLONIO 98 search for neutrino oscillations at 1.1 km fixed distance from Chooz reactors. They use $\overline{\nu}_e p \rightarrow e^+ n$ in Gd-loaded scintillator target. APOLLONIO 99 supersedes APOLLONIO 98.

[151] GREENWOOD 96 search for neutrino oscillations at 18 m and 24 m from the reactor at Savannah River.

[152] DECLAIS 94 result based on integral measurement of neutrons only. Result is ratio of measured cross section to that expected in standard V-A theory. Replaced by ACHKAR 95.

[153] KWON 81 represents an analysis of a larger set of data from the same experiment as BOEHM 80.

[154] REINES 80 involves comparison of neutral- and charged-current reactions $\overline{\nu}_e d \rightarrow n p \overline{\nu}_e$ and $\overline{\nu}_e d \rightarrow n n e^+$ respectively. Combined analysis of reactor $\overline{\nu}_e$ experiments was performed by SILVERMAN 81.

[155] The two REINES 80 values correspond to the calculated $\overline{\nu}_e$ fluxes of AVIGNONE 80 and DAVIS 79 respectively.

$\overline{\nu}_e \not\rightarrow \overline{\nu}_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<7 $\times 10^{-4}$ (CL = 90%) [$<9 \times 10^{-4}$ eV^2 (CL = 90%) OUR 1998 BEST LIMIT]					
<0.0007	90	[156] APOLLONIO	99	CHOZ	Chooz reactors 1 km
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0011	90	[157] BOEHM	00		Palo Verde react. 0.8 km
<0.01	90	[158] ACHKAR	95	CNTR	Bugey reactor
<0.0075	90	[159] VIDYAKIN	94		Krasnoyark reactors
<0.04	90	[160] AFONIN	88	CNTR	Rovno reactor
<0.014	68	[161] VIDYAKIN	87		$\overline{\nu}_e p \rightarrow e^+ n$
<0.019	90	[162] ZACEK	86		Gösgen reactor

[156] APOLLONIO 99 search for neutrino oscillations at 1.1 km fixed distance from Chooz reactors. They use $\overline{\nu}_e p \rightarrow e^+ n$ in Gd-loaded scintillator target. APOLLONIO 99

supersedes APOLLONIO 98. This is the most sensitive search in terms of $\Delta(m^2)$ for $\overline{\nu}_e$ disappearance.

[157] BOEHM 00 is a disappearance search for neutrino oscillations at 0.75 and 0.89 km distance from Palo Verde reactors. The detection reaction is $\overline{\nu}_e\, p \to e^+ n$ in a segmented Gd loaded scintillator target. Result is less restrictive than APOLLONIO 99.

[158] ACHKAR 95 bound is for L=15, 40, and 95 m.

[159] VIDYAKIN 94 bound is for L=57.0 m, 57.6 m, and 231.4 m. Supersedes VIDYAKIN 90.

[160] AFONIN 86 and AFONIN 87 also give limits on $\sin^2(2\theta)$ for intermediate values of $\Delta(m^2)$. (See also KETOV 92). Supersedes AFONIN 87, AFONIN 86, AFONIN 85, AFONIN 83, and BELENKII 83.

[161] VIDYAKIN 87 bound is for L = 32.8 and 92.3 m distance from two reactors.

[162] This bound is from data for L=37.9 m, 45.9 m, and 64.7 m.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[163] ACHKAR	95	CNTR	For $\Delta(m^2) = 0.6$ eV^2
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.21	90	[164] BOEHM	00		Palo Verde react. 0.8 km
<0.10	90	[165] APOLLONIO	99	CHOZ	Chooz reactors 1 km
<0.24	90	[166] GREENWOOD	96		
<0.04	90	[166] GREENWOOD	96		For $\Delta(m^2) = 1.0$ eV^2
<0.087	68	[167] VYRODOV	95	CNTR	For $\Delta(m^2)$ >2 eV^2
<0.15	90	[168] VIDYAKIN	94		For $\Delta(m^2) > 5.0 \times 10^{-2}$ eV^2
<0.2	90	[169] AFONIN	88	CNTR	$\overline{\nu}_e\, p \to e^+ n$
<0.14	68	[170] VIDYAKIN	87		$\overline{\nu}_e\, p \to e^+ n$
<0.21	90	[171] ZACEK	86		$\overline{\nu}_e\, p \to e^+ n$
<0.19	90	[172] ZACEK	85		Gösgen reactor
<0.16	90	[173] GABATHULER	84		$\overline{\nu}_e\, p \to e^+ n$

[163] ACHKAR 95 bound is from data for L=15, 40, and 95 m distance from the Bugey reactor.

[164] BOEHM 00 search for neutrino oscillations at 0.75 and 0.89 km distance from Pao Verde reactors.

[165] APOLLONIO 99 search for neutrino oscillations at 1.1 km fixed distance from Chooz reactors.

[166] GREENWOOD 96 search for neutrino oscillations at 18 m and 24 m from the reactor at Savannah River by observing $\overline{\nu}_e\, p \to e^+ n$ in a Gd loaded scintillator target. Their region of sensitivity in $\Delta(m^2)$ and $\sin^2 2\theta$ is already excluded by ACHKAR 95.

[167] The VYRODOV 95 bound is from data for L=15 m distance from the Bugey-5 reactor.

[168] The VIDYAKIN 94 bound is from data for L=57.0 m, 57.6 m, and 231.4 m from three reactors in the Krasnoyark Reactor complex.

[169] Several different methods of data analysis are used in AFONIN 88. We quote the most stringent limits. Different upper limits on $\sin^2 2\theta$ apply at intermediate values of $\Delta(m^2)$. Supersedes AFONIN 87, AFONIN 85, and BELENKII 83.

[170] VIDYAKIN 87 bound is for L = 32.8 and 92.3 m distance from two reactors.

[171] This bound is from data for L=37.9 m, 45.9 m, and 64.7 m distance from Gosgen reactor.

[172] ZACEK 85 gives two sets of bounds depending on what assumptions are used in the data analysis. The bounds in figure 3(a) of ZACEK 85 are progressively poorer for large $\Delta(m^2)$ whereas those of figure 3(b) approach a constant. We list the latter. Both sets of bounds use combination of data from 37.9, 45.9, and 64.7m distance from reactor. ZACEK 85 states "Our experiment excludes this area (the oscillation parameter region allowed by the Bugey data, CAVAIGNAC 84) almost completely, thus disproving the indications of neutrino oscillations of CAVAIGNAC 84 with a high degree of confidence."

[173] This bound comes from a combination of the VUILLEUMIER 82 data at distance 37.9m from Gosgen reactor and new data at 45.9m.

(H) Accelerator neutrino appearance experiments

$\nu_e \rightarrow \nu_\tau$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 0.77 (CL = 90%) [<9 eV^2 (CL = 90%) OUR 1998 BEST LIMIT]					
< 0.77	90	[174] ARMBRUSTER	98	KARM	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<17	90	NAPLES	99	CCFR	FNAL
<44	90	TALEBZADEH	87	HLBC	BEBC
< 9	90	USHIDA	86C	EMUL	FNAL

[174] ARMBRUSTER 98 use KARMEN detector with ν_e from muon decay at rest and observe $^{12}C(\nu_e,e^-)^{12}N_{gs}$ essentially free from this background. The reported limits on the parameters of ν_e disappearance are not competitive. A three-flavor analysis is also presented.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.21 (CL = 90%) [<0.25 (CL = 90%) OUR 1998 BEST LIMIT]					
<0.21	90	NAPLES	99	CCFR	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.338	90	[175] ARMBRUSTER	98	KARM	
<0.36	90	TALEBZADEH	87	HLBC	BEBC
<0.25	90	[176] USHIDA	86C	EMUL	FNAL

[175] See foonote in preeding table (ARMBRUSTER 98) for further details, and see the paper for a plot showing allowed regions. A three-flavor analysis is also presented here.

[176] USHIDA 86C published result is $\sin^2 2\theta < 0.12$. The quoted result is corrected for a numerical mistake incurred in calculating the expected number of ν_e CC events, normalized to the total number of neutrino interactions (3886) rather than to the total number of ν_μ CC events (1870).

$\overline{\nu}_e \rightarrow \overline{\nu}_\tau$

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.7	90	[177] FRITZE	80	HYBR	BEBC CERN SPS

[177] Authors give $P(\nu_e \rightarrow \nu_\tau) < 0.35$, equivalent to above limit.

$\nu_\mu \rightarrow \nu_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.09	90	ANGELINI	86	HLBC	BEBC CERN PS

• • • We do not use the following data for averages, fits, limits, etc. • • •

0.03 to 0.3	95	[178]	ATHANASSO...	98	LSND	$\nu_\mu \rightarrow \nu_e$
<2.3	90	[179]	LOVERRE	96		CHARM/CDHS
<0.9	90		VILAIN	94C	CHM2	CERN SPS
<0.1	90		BLUMENFELD	89	CNTR	
<1.3	90		AMMOSOV	88	HLBC	SKAT at Serpukhov
<0.19	90		BERGSMA	88	CHRM	
		[180]	LOVERRE	88	RVUE	
<2.4	90		AHRENS	87	CNTR	BNL AGS
<1.8	90		BOFILL	87	CNTR	FNAL
<2.2	90	[181]	BRUCKER	86	HLBC	15-ft FNAL
<0.43	90		AHRENS	85	CNTR	BNL AGS E734
<0.20	90		BERGSMA	84	CHRM	
<1.7	90		ARMENISE	81	HLBC	GGM CERN PS
<0.6	90		BAKER	81	HLBC	15-ft FNAL
<1.7	90		ERRIQUEZ	81	HLBC	BEBC CERN PS
<1.2	95		BLIETSCHAU	78	HLBC	GGM CERN PS
<1.2	95		BELLOTTI	76	HLBC	GGM CERN PS

[178] ATHANASSOPOULOS 98 is a search for the $\nu_\mu \rightarrow \nu_e$ oscillations using ν_μ from π^+ decay in flight. The 40 observed beam-on electron events are consistent with $\nu_e \mathrm{C} \rightarrow e^- \mathrm{X}$; the expected background is 21.9 ± 2.1. Authors interpret this excess as evidence for an oscillation signal corresponding to oscillations with probability $(0.26 \pm 0.10 \pm 0.05)$%. Although the significance is only 2.3 σ, this measurement is an important and consistent cross check of ATHANASSOPOULOS 96 who reported evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations from μ^+ decay at rest. See also ATHANASSOPOULOS 98B.

[179] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

[180] LOVERRE 88 reports a less stringent, indirect limit based on theoretical analysis of neutral to charged current ratios.

[181] 15ft bubble chamber at FNAL.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%		DOCUMENT ID		TECN	COMMENT
< 3.0	90	[182]	LOVERRE	96		CHARM/CDHS
< 2.5	90		AMMOSOV	88	HLBC	SKAT at Serpukhov
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.0005 to 0.03	95	[183]	ATHANASSO...	98	LSND	$\nu_\mu \rightarrow \nu_e$
< 9.4	90		VILAIN	94C	CHM2	CERN SPS
< 5.6	90	[184]	VILAIN	94C	CHM2	CERN SPS
< 16	90		BLUMENFELD	89	CNTR	
< 8	90		BERGSMA	88	CHRM	$\Delta(m^2) \geq 30$ eV^2
		[185]	LOVERRE	88	RVUE	
< 10	90		AHRENS	87	CNTR	BNL AGS
< 15	90		BOFILL	87	CNTR	FNAL
< 20	90	[186]	ANGELINI	86	HLBC	BEBC CERN PS

20 to 40		[187] BERNARDI	86B	CNTR	$\Delta(m^2)$=5–10
< 11	90	[188] BRUCKER	86	HLBC	15-ft FNAL
< 3.4	90	AHRENS	85	CNTR	BNL AGS E734
<240	90	BERGSMA	84	CHRM	
< 10	90	ARMENISE	81	HLBC	GGM CERN PS
< 6	90	BAKER	81	HLBC	15-ft FNAL
< 10	90	ERRIQUEZ	81	HLBC	BEBC CERN PS
< 4	95	BLIETSCHAU	78	HLBC	GGM CERN PS
< 10	95	BELLOTTI	76	HLBC	GGM CERN PS

[182] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

[183] ATHANASSOPOULOS 98 report (0.26 ± 0.10 ± 0.05)% for the oscillation probability; the value of $\sin^2 2\theta$ for large Δm^2 is deduced from this probability. See footnote in preceding table for further details, and see the paper for a plot showing allowed regions. If effect is due to oscillation, it is most likely to be intermediate $\sin^2 2\theta$ and Δm^2. See also ATHANASSOPOULOS 98B.

[184] VILAIN 94C limit derived by combining the ν_μ and $\overline{\nu}_\mu$ data assuming *CP* conservation.

[185] LOVERRE 88 reports a less stringent, indirect limit based on theoretical analysis of neutral to charged current ratios.

[186] ANGELINI 86 limit reaches 13×10^{-3} at $\Delta(m^2) \approx 2$ eV^2.

[187] BERNARDI 86B is a typical fit to the data, assuming mixing between two species. As the authors state, this result is in conflict with earlier upper bounds on this type of neutrino oscillations.

[188] 15ft bubble chamber at FNAL.

$\overline{\nu}_\mu \to \overline{\nu}_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.14	90	[189] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.05–0.08	90	[190] ATHANASSO...	96	LSND	LAMPF
0.048–0.090	80	[191] ATHANASSO...	95		
<0.07	90	[192] HILL	95		
<0.9	90	VILAIN	94C	CHM2	CERN SPS
<3.1	90	BOFILL	87	CNTR	FNAL
<2.4	90	TAYLOR	83	HLBC	15-ft FNAL
<0.91	90	[193] NEMETHY	81B	CNTR	LAMPF
<1	95	BLIETSCHAU	78	HLBC	GGM CERN PS

[189] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$. FREEDMAN 93 replaces DURKIN 88.

[190] ATHANASSOPOULOS 96 is a search for $\overline{\nu}_e$ 30 m from LAMPF beam stop. Neutrinos originate mainly from π^+ decay at rest. $\overline{\nu}_e$ could come from either $\overline{\nu}_\mu \to \overline{\nu}_e$ or $\nu_e \to \overline{\nu}_e$; our entry assumes the first interpretation. They are detected through $\overline{\nu}_e p \to e^+ n$ (20 MeV $< E_{e^+} <$ 60 MeV) in delayed coincidence with $np \to d\gamma$. Authors observe 51 ± 20 ± 8 total excess events over an estimated background 12.5 ± 2.9. ATHANASSOPOULOS 96B is a shorter version of this paper.

[191] ATHANASSOPOULOS 95 error corresponds to the 1.6σ band in the plot. The expected background is 2.7 ± 0.4 events. Corresponds to an oscillation probability of

$(0.34^{+0.20}_{-0.18} \pm 0.07)\%$. For a different interpretation, see HILL 95. Replaced by ATHANASSOPOULOS 96.

[192] HILL 95 is a report by one member of the LSND Collaboration, reporting a different conclusion from the analysis of the data of this experiment (see ATHANASSOPOULOS 95). Contrary to the rest of the LSND Collaboration, Hill finds no evidence for the neutrino oscillation $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ and obtains only upper limits.

[193] In reaction $\overline{\nu}_e p \rightarrow e^+ n$.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	95	BLIETSCHAU	78	HLBC	GGM CERN PS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.0062 \pm 0.0024 \pm 0.0010$		[194] ATHANASSO...	96	LSND	LAMPF
0.003–0.012	80	[195] ATHANASSO...	95		
<0.006	90	[196] HILL	95		
<4.8	90	VILAIN	94C	CHM2	CERN SPS
<5.6	90	[197] VILAIN	94C	CHM2	CERN SPS
<0.024	90	[198] FREEDMAN	93	CNTR	LAMPF
<0.04	90	BOFILL	87	CNTR	FNAL
<0.013	90	TAYLOR	83	HLBC	15-ft FNAL
<0.2	90	[199] NEMETHY	81B	CNTR	LAMPF

[194] ATHANASSOPOULOS 96 reports $(0.31 \pm 0.12 \pm 0.05)\%$ for the oscillation probability; the value of $\sin^2 2\theta$ for large $\Delta(m^2)$ should be twice this probability. See footnote in preceding table for further details, and see the paper for a plot showing allowed regions.

[195] ATHANASSOPOULOS 95 error corresponds to the 1.6σ band in the plot. The expected background is 2.7 ± 0.4 events. Corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)\%$. For a different interpretation, see HILL 95. Replaced by ATHANASSOPOULOS 96.

[196] HILL 95 is a report by one member of the LSND Collaboration, reporting a different conclusion from the analysis of the data of this experiment (see ATHANASSOPOULOS 95). Contrary to the rest of the LSND Collaboration, Hill finds no evidence for the neutrino oscillation $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ and obtains only upper limits.

[197] VILAIN 94C limit derived by combining the ν_μ and $\overline{\nu}_\mu$ data assuming *CP* conservation.

[198] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$. FREEDMAN 93 replaces DURKIN 88.

[199] In reaction $\overline{\nu}_e p \rightarrow e^+ n$.

$\nu_\mu(\overline{\nu}_\mu) \rightarrow \nu_e(\overline{\nu}_e)$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.075	90	BORODOV...	92	CNTR	BNL E776
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	90	[200] ROMOSAN	97	CCFR	FNAL

[200] ROMOSAN 97 uses wideband beam with a 0.5 km decay region.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1.8	90	[201] ROMOSAN	97	CCFR	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.8	90	[202] MCFARLAND	95	CCFR	FNAL
<3	90	BORODOV...	92	CNTR	BNL E776

[201] ROMOSAN 97 uses wideband beam with a 0.5 km decay region.

[202] MCFARLAND 95 state that "This result is the most stringent to date for $250 < \Delta(m^2) < 450$ eV^2 and also excludes at 90%CL much of the high $\Delta(m^2)$ region favored by the recent LSND observation." See ATHANASSOPOULOS 95 and ATHANASSOPOULOS 96.

$\nu_\mu \rightarrow \nu_\tau$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 1.1 (CL = 90%) [<0.9 eV^2 (CL = 90%) OUR 1998 BEST LIMIT]					
< 1.1	90	[203] ESKUT	98B	CHRS	CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.2	90	[204] ASTIER	99	NOMD	CERN SPS
< 1.4	90	[205] ALTEGOER	98B	NOMD	CERN SPS
< 1.5	90	[206] ESKUT	98	CHRS	CERN SPS
< 3.3	90	[207] LOVERRE	96		CHARM/CDHS
< 1.4	90	MCFARLAND	95	CCFR	FNAL
< 4.5	90	BATUSOV	90B	EMUL	FNAL
<10.2	90	BOFILL	87	CNTR	FNAL
< 6.3	90	BRUCKER	86	HLBC	15-ft FNAL
< 0.9	90	USHIDA	86C	EMUL	FNAL
< 4.6	90	ARMENISE	81	HLBC	GGM CERN SPS
< 3	90	BAKER	81	HLBC	15-ft FNAL
< 6	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
< 3	90	USHIDA	81	EMUL	FNAL

[203] ESKUT 98B search for $\tau^- \rightarrow \mu^- \nu_\tau \overline{\nu}_\mu$ or $h^- \nu_\tau \overline{\nu}_\mu$, where h^- is a negatively charged hadron. The μ^- sample is somewhat larger than in ESKUT 98, which this result supersedes. Bayesian limit.

[204] ASTIER 99 limits are based on data corresponding to $\sim 950000\, \nu_\mu$CC interactions in the 1995, 1996, and (most) 1997 runs. This is a "blind" analysis using the FELDMAN 98 classical CL approach, and other algorithms have also been improved since ALTEGOER 98B.

[205] ALTEGOER 98B is the NOMAD 1995 data sample result, searching for events with $\tau^- \rightarrow e^- \nu_\tau \overline{\nu}_e$, hadron$^-$ ν_τ, or $\pi^- \pi^+ \pi^-$ decay modes using classical CL approach of FELDMAN 98.

[206] ESKUT 98 search for events with one μ^- with indication of a kink from τ^- decay in the nuclear emulsion. No candidates were found in a 31,423 event subsample.

[207] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0012 (CL = 90%)	[<0.004 (CL = 90%) OUR 1998 BEST LIMIT]				
<0.0012	90	[208] ASTIER	99	NOMD	CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0042	90	[209] ALTEGOER	98B	NOMD	CERN SPS
<0.0035	90	[210] ESKUT	98	CHRS	CERN SPS
<0.0018	90	[211] ESKUT	98B	CHRS	CERN SPS
<0.006	90	[212] LOVERRE	96		CHARM/CDHS
<0.0081	90	MCFARLAND	95	CCFR	FNAL
<0.06	90	BATUSOV	90B	EMUL	FNAL
<0.34	90	BOFILL	87	CNTR	FNAL
<0.088	90	BRUCKER	86	HLBC	15-ft FNAL
<0.004	90	USHIDA	86C	EMUL	FNAL
<0.11	90	BALLAGH	84	HLBC	15-ft FNAL
<0.017	90	ARMENISE	81	HLBC	GGM CERN SPS
<0.06	90	BAKER	81	HLBC	15-ft FNAL
<0.05	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
<0.013	90	USHIDA	81	EMUL	FNAL

[208] ASTIER 99 limits are based on data corresponding to $\sim$ 950000 ν_μCC interactions in the 1995, 1996, and (most) 1997 runs. This is a "blind" analysis using the FELDMAN 98 classical CL approach, and other algorithms have also been improved since ALTEGOER 98B.

[209] ALTEGOER 98B is the NOMAD 1995 data sample result, searching for events with $\tau^- \rightarrow e^- \nu_\tau \overline{\nu}_e$, hadron$^-$ ν_τ, or $\pi^-\pi^+\pi^-$ decay modes using classical CL approach of FELDMAN 98.

[210] ESKUT 98 search for events with one μ^- with indication of a kink from τ^- decay in the nuclear emulsion. No candidates were found in a 31,423 event subsample.

[211] ESKUT 98B search for $\tau^- \rightarrow \mu^- \nu_\tau \overline{\nu}_\mu$ or $h^- \nu_\tau \overline{\nu}_\mu$, where h^- is a negatively charged hadron. The μ^- sample is somewhat larger than in ESKUT 98, which this result supersedes. Bayesian limit.

[212] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

$\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<2.2	90	ASRATYAN	81	HLBC	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.4	90	MCFARLAND	95	CCFR	FNAL
<6.5	90	BOFILL	87	CNTR	FNAL
<7.4	90	TAYLOR	83	HLBC	15-ft FNAL

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.4 × 10^{-2}	90	ASRATYAN	81	HLBC	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0081	90	MCFARLAND	95	CCFR	FNAL
<0.15	90	BOFILL	87	CNTR	FNAL
<8.8 × 10^{-2}	90	TAYLOR	83	HLBC	15-ft FNAL

$\nu_\mu(\overline{\nu}_\mu) \to \nu_\tau(\overline{\nu}_\tau)$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	[213] GRUWE	93	CHM2	CERN SPS

[213] GRUWE 93 is a search using the CHARM II detector in the CERN SPS wide-band neutrino beam for $\nu_\mu \to \nu_\tau$ and $\overline{\nu}_\mu \to \overline{\nu}_\tau$ oscillations signalled by quasi-elastic ν_τ and $\overline{\nu}_\tau$ interactions followed by the decay $\tau \to \nu_\tau \pi$. The maximum sensitivity in $\sin^2 2\theta$ ($< 6.4 \times 10^{-3}$ at the 90% CL) is reached for $\Delta(m^2) \simeq 50$ eV^2.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<8	90	[214] GRUWE	93	CHM2	CERN SPS

[214] GRUWE 93 is a search using the CHARM II detector in the CERN SPS wide-band neutrino beam for $\nu_\mu \to \nu_\tau$ and $\overline{\nu}_\mu \to \overline{\nu}_\tau$ oscillations signalled by quasi-elastic ν_τ and $\overline{\nu}_\tau$ interactions followed by the decay $\tau \to \nu_\tau \pi$. The maximum sensitivity in $\sin^2 2\theta$ ($< 6.4 \times 10^{-3}$ at the 90% CL) is reached for $\Delta(m^2) \simeq 50$ eV^2.

$\nu_e \to (\overline{\nu}_e)_L$

This is a limit on lepton family-number violation and total lepton-number violation. $(\overline{\nu}_e)_L$ denotes a hypothetical left-handed $\overline{\nu}_e$. The bound is quoted in terms of Δ (m^2), $\sin(2\theta)$, and α, where α denotes the fractional admixture of ($V+A$) charged current.

$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.14	90	[215] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7	90	[216] COOPER	82	HLBC	BEBC CERN SPS

[215] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$.

[216] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.032	90	[217] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	[218] COOPER	82	HLBC	BEBC CERN SPS

[217] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$.

[218] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\nu_\mu \rightarrow (\overline{\nu}_e)_L$

See note above for $\nu_e \rightarrow (\overline{\nu}_e)_L$ limit

$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.16	90	[219] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.7	90	[220] COOPER	82	HLBC	BEBC CERN SPS

[219] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$. The limit on $\Delta(m^2)$ is better than the CERN BEBC experiment, but the limit on $\sin^2\theta$ is almost a factor of 100 less sensitive.
[220] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.001	90	[221] COOPER	82	HLBC	BEBC CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.07	90	[222] FREEDMAN	93	CNTR	LAMPF

[221] COOPER 82 states that existing bounds on V+A currents require α to be small.
[222] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$. The limit on $\Delta(m^2)$ is better than the CERN BEBC experiment, but the limit on $\sin^2\theta$

(I) Disappearance experiments with accelerator & radioactive source neutrinos

$\nu_e \not\rightarrow \nu_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 0.18 (CL = 90%)	[<0.17 eV^2 (CL = 90%) OUR 1998 BEST LIMIT]				
< 0.18	90	[223] HAMPEL	98	GALX	^{51}Cr source
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<40	90	[224] BORISOV	96	CNTR	IHEP-JINR detector
<14.9	90	BRUCKER	86	HLBC	15-ft FNAL
< 8	90	BAKER	81	HLBC	15-ft FNAL
<56	90	DEDEN	81	HLBC	BEBC CERN SPS
<10	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
<2.3 OR >8	90	NEMETHY	81B	CNTR	LAMPF

[223] HAMPEL 98 analyzed the GALLEX calibration results with ^{51}Cr neutrino sources and updates the BAHCALL 95 analysis result. They also gave 95% and 99% CL limits of < 0.2 and < 0.22, respectively.
[224] BORISOV 96 exclusion curve extrapolated to obtain this value; however, it does not have the right curvature in this region.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7 × 10^{-2}	90	[225] ERRIQUEZ	81	HLBC	BEBC CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.4	90	[226] HAMPEL	98	GALX	^{51}Cr source
<0.115	90	[227] BORISOV	96	CNTR	$\Delta(m^2) = 175$ eV^2
<0.54	90	BRUCKER	86	HLBC	15-ft FNAL
<0.6	90	BAKER	81	HLBC	15-ft FNAL
<0.3	90	[225] DEDEN	81	HLBC	BEBC CERN SPS

[225] Obtained from a Gaussian centered in the unphysical region.
[226] HAMPEL 98 analyzed the GALLEX calibration results with ^{51}Cr neutrino sources and updates the BAHCALL 95 analysis result. They also gave 95% and 99% CL limits of < 0.45 and < 0.56, respectively.
[227] BORISOV 96 sets less stringent limits at large $\Delta(m^2)$, but exclusion curve does not have clear asymptotic behavior.

$\nu_\mu \not\to \nu_\mu$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.23 OR >1500 OUR LIMIT					
<0.23 OR >100	90	DYDAK	84	CNTR	
<13 OR >1500	90	STOCKDALE	84	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.29 OR >22	90	BERGSMA	88	CHRM	
<7	90	BELIKOV	85	CNTR	Serpukhov
<8.0 OR >1250	90	STOCKDALE	85	CNTR	
<0.29 OR >22	90	BERGSMA	84	CHRM	
<8.0	90	BELIKOV	83	CNTR	

$\sin^2(2\theta)$ for $\Delta(m^2) = 100\text{eV}^2$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[228] STOCKDALE	85	CNTR	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.17	90	[229] BERGSMA	88	CHRM	
<0.07	90	[230] BELIKOV	85	CNTR	Serpukhov
<0.27	90	[229] BERGSMA	84	CHRM	CERN PS
<0.1	90	[231] DYDAK	84	CNTR	CERN PS
<0.02	90	[232] STOCKDALE	84	CNTR	FNAL
<0.1	90	[233] BELIKOV	83	CNTR	Serpukhov

[228] This bound applies for $\Delta(m^2) = 100$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $8 < \Delta(m^2) < 1250$ eV^2.
[229] This bound applies for $\Delta(m^2) = 0.7$–9. eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $0.28 < \Delta(m^2) < 22$ eV^2.
[230] This bound applies for a wide range of $\Delta(m^2) > 7$ eV^2. For some values of $\Delta(m^2)$, the value is less stringent; the least restrictive, nontrivial bound occurs approximately at $\Delta(m^2) = 300$ eV^2 where $\sin^2(2\theta) < 0.13$ at CL = 90%.
[231] This bound applies for $\Delta(m^2) = 1.$–10. eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $0.23 < \Delta(m^2) < 90$ eV^2.
[232] This bound applies for $\Delta(m^2) = 110$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $13 < \Delta(m^2) < 1500$ eV^2.
[233] Bound holds for $\Delta(m^2) = 20$–1000 eV^2.

$\overline{\nu}_\mu \not\to \overline{\nu}_\mu$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN
<7 OR >1200 OUR LIMIT				
<7 OR >1200	90	STOCKDALE	85	CNTR

$\sin^2(2\theta)$ for 190 eV^2 $<$ $\Delta(m^2)$ $<$ 320 eV^2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[234] STOCKDALE	85	CNTR	FNAL

[234] This bound applies for $\Delta(m^2)$ between 190 and 320 or = 530 eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for 7 < $\Delta(m^2)$ <1200 eV^2.

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ABREU	99O	EPJ C8 41	P. Abreu *et al.*	(DELPHI Collab.)
ACCIARRI	99K	PL B461 397	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99L	PL B462 354	M. Acciarri *et al.*	(L3 Collab.)
ALLISON	99	PL B449 137	W.W.M. Allison *et al.*	(Soudan 2 Collab.)
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FUKUDA	99	PRL 82 1810	Y. Fukuda *et al.*	(Super-Kamiokande Collab.)
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FUKUDA	99C	PRL 82 2644	Y. Fukuda *et al.*	(Super-Kamiokande Collab.)
FUKUDA	99D	PL B467 185	Y. Fukuda *et al.*	(Super-Kamiokande Collab.)
HAMPEL	99	PL B447 127	W. Hampel *et al.*	(GALLEX Collab.)
HOLZSCHUH	99	PL B451 247	E. Holzschuh *et al.*	
NAPLES	99	PR D59 031101	D. Naples *et al.*	(CCFR Collab.)
VAITAITIS	99	PRL 83 4943	A. Vaitaitis *et al.*	(CCFR Collab.)
ACKERSTAFF	98C	EPJ C1 45	K. Ackerstaff *et al.*	(OPAL Collab.)
ALESSAND...	98	PL B433 156	A. Alessandrello *et al.*	
ALTEGOER	98B	PL B431 219	S. Altegoer *et al.*	(NOMAD Collab.)
AMBROSIO	98	PL B434 451	M. Ambrosio *et al.*	(MACRO Collab.)
APOLLONIO	98	PL B420 397	M. Apollonio *et al.*	(CHOOZ Collab.)
ARMBRUSTER	98	PR C57 3414	B. Armbruster *et al.*	(KARMEN Collab.)
ASSAMAGAN	98	PL B434 158	K. Assamagan *et al.*	
ATHANASSO...	98	PRL 81 1774	C. Athanassopoulos *et al.*	(LSND Collab.)
ATHANASSO...	98B	PR C58 2489	C. Athanassopoulos *et al.*	(LSND Collab.)
CLEVELAND	98	APJ 496 505	B.T. Cleveland *et al.*	(Homestake Collab.)
ESKUT	98	PL B424 202	E. Eskut *et al.*	(CHORUS Collab.)
ESKUT	98B	PL B434 205	E. Eskut *et al.*	(CHORUS Collab.)
FELDMAN	98	PR D57 3873	G.J. Feldman, R.D. Cousins	
FUKUDA	98	PL B433 9	Y. Fukuda *et al.*	(Super-Kamiokande Collab.)
FUKUDA	98B	PRL 81 1158	Y. Fukuda *et al.*	(Super-Kamiokande Collab.)
FUKUDA	98C	PRL 81 1562	Y. Fukuda *et al.*	(Super-Kamiokande Collab.)
FUKUDA	98E	PL B436 33	Y. Fukuda *et al.*	(Super-Kamiokande Collab.)
HAMPEL	98	PL B420 114	W. Hampel *et al.*	(GALLEX Collab.)
HATAKEYAMA	98	PRL 81 2016	S. Hatakeyama *et al.*	(Kamiokande Collab.)
HINDI	98	PR C58 2512	M.M. Hindi *et al.*	
LUESCHER	98	PL B434 407	R. Luescher *et al.*	
OYAMA	98	PR D57 R6594	Y. Oyama	
PDG	98	EPJ C3 1	C. Caso *et al.*	
ABREU	97I	ZPHY C74 57	P. Abreu *et al.*	(DELPHI Collab.)
Also	97L	ZPHY C75 580 erratum	P. Abreu *et al.*	(DELPHI Collab.)
ALLISON	97	PL B391 491	W.W.M. Allison *et al.*	(Soudan 2 Collab.)
ALSTON-...	97	PR C55 474	M. Alston-Garnjost *et al.*	(LBL, MTHO+)
BARABASH	97	ZPHY A357 351	A.S. Barabash *et al.*	(ITEP, BCEN)

BAUDIS	97	PL B407 219	L. Baudis *et al.*	(MPIH, KIAE, SASSO)
CLARK	97	PRL 79 345	R. Clark *et al.*	(IMB Collab.)
DESILVA	97	PR C56 2451	A. de Silva *et al.*	(UCI)
GUENTHER	97	PR D55 54	M. Gunther *et al.*	(MPIH, KIAE, SASSO)
ROMOSAN	97	PRL 78 2912	A. Romosan *et al.*	(CCFR Collab.)
ALESSAND...	96B	NPBPS 48 238	A. Alessandrello *et al.*	(MILA, SASSO)
ARNOLD	96	ZPHY C72 239	R. Arnold *et al.*	(BCEN, CAEN, JINR+)
ATHANASSO...	96	PR C54 2685	C. Athanassopoulos *et al.*	(LSND Collab.)
ATHANASSO...	96B	PRL 77 3082	C. Athanassopoulos *et al.*	(LSND Collab.)
BALYSH	96	PRL 77 5186	A. Balysh *et al.*	(KIAE, UCI, CIT)
BORISOV	96	PL B369 39	A.A. Borisov *et al.*	(SERP, JINR)
BRYMAN	96	PR D53 558	D.A. Bryman, T. Numao	(TRIU)
BUSKULIC	96S	PL B384 439	D. Buskulic *et al.*	(ALEPH Collab.)
EJIRI	96	NP A611 85	H. Ejiri *et al.*	(OSAK)
FUKUDA	96	PRL 77 1683	Y. Fukuda *et al.*	(Kamiokande Collab.)
FUKUDA	96B	PL B388 397	Y. Fukuda *et al.*	(Kamiokande Collab.)
GREENWOOD	96	PR D53 6054	Z.D. Greenwood *et al.*	(UCI, SVR, SCUC)
HAMPEL	96	PL B388 384	W. Hampel *et al.*	(GALLEX Collab.)
LOVERRE	96	PL B370 156	P.F. Loverre	
TAKAOKA	96	PR C53 1557	N. Takaoka, Y. Motomura, K. Nagao	(KYUSH, OKAY)
WIETFELDT	96	PRPL 273 149	F.E. Wietfeldt, E.B. Norman	(LBL)
ACHKAR	95	NP B434 503	B. Achkar *et al.*	(SING, SACLD, CPPM, CDEF+)
AHLEN	95	PL B357 481	S.P. Ahlen *et al.*	(MACRO Collab.)
ARMBRUSTER	95	PL B348 19	B. Armbruster *et al.*	(KARMEN Collab.)
ARNOLD	95	JETPL 61 170	R.G. Arnold *et al.*	(NEMO Collab.)
		Translated from ZETFP 61 168.		
ATHANASSO...	95	PRL 75 2650	C. Athanassopoulos *et al.*	(LSND Collab.)
BAHCALL	95	PL B348 121	J.N. Bahcall, P.I. Krastev, E. Lisi	(IAS)
BAHRAN	95	PL B354 481	M.Y. Bahran, G.R. Kalbfleisch	(OKLA)
BALYSH	95	PL B356 450	A. Balysh *et al.*	(MPIH, KIAE, SASSO)
BARABASH	95	PL B345 408	A.S. Barabash *et al.*	(ITEP, SCUC, PNL+)
BILGER	95	PL B363 41	R. Bilger *et al.*	(TUBIN, KARLE, PSI)
BURACHAS	95	PAN 58 153	S.F. Burachas *et al.*	(KIEV)
		Translated from YAF 58 195.		
DANEVICH	95	PL B344 72	F.A. Danevich *et al.*	(KIEV)
DASSIE	95	PR D51 2090	D. Dassie *et al.*	(NEMO Collab.)
DAUM	95	ZPHY C66 417	K. Daum *et al.*	(FREJUS Collab.)
DAUM	95B	PL B361 179	M. Daum *et al.*	(PSI, VIRG)
EJIRI	95	JPSJ 64 339	H. Ejiri *et al.*	(OSAK, KIEV)
FARGION	95	PR D52 1828	D. Fargion *et al.*	(ROMA, KIAM, MPEI)
GALLAS	95	PR D52 6	E. Gallas *et al.*	(MSU, FNAL, MIT, FLOR)
GARCIA	95	PR D51 1458	E. Garcia *et al.*	(ZARA, SCUC, PNL)
GEORGADZE	95	PAN 58 1093		
		Translated from YAF 58 1170.		
HAGNER	95	PR D52 1343	C. Hagner *et al.*	(MUNT, LAPP, CPPM)
HIDDEMANN	95	JP G21 639	K.H. Hiddemann, H. Daniel, O. Schwentker	(MUNT)
HILL	95	PRL 75 2654	J.E. Hill	(PENN)
KOBAYASHI	95	NP A586 457	M. Kobayashi, M. Kobayashi	(KEK, SAGA)
MCFARLAND	95	PRL 75 3993	K.S. McFarland *et al.*	(CCFR Collab.)
VILAIN	95C	PL B351 387	P. Vilain *et al.*	(CHARM II Collab.)
Also	95	PL B343 453	P. Vilain *et al.*	(CHARM II Collab.)
VYRODOV	95	JETPL 61 163	V.N. Vyrodov *et al.*	(KIAE, LAPP, CDEF)
		Translated from ZETFP 61 161.		
ABDURASHI...	94	PL B328 234	J.N. Abdurashitov *et al.*	(SAGE Collab.)
BALYSH	94	PL B322 176	A. Balysh *et al.*	(MPIH, KIAE, SASSO)
BECK	94	PL B336 141	M. Beck *et al.*	(MPIH, KIAE, SASSO)
DECLAIS	94	PL B338 383	Y. Declais *et al.*	
FUKUDA	94	PL B335 237	Y. Fukuda *et al.*	(Kamiokande Collab.)
KONOPLICH	94	PAN 57 425	R.V. Konoplich, M.Y. Khlopov	(MPEI)
PDG	94	PR D50 1173	L. Montanet *et al.*	(CERN, LBL, BOST+)
PIEPKE	94	NP A577 493	A. Piepke *et al.*	(MPIH, ITEP)
SMIRNOV	94	PR D49 1389	A.Y. Smirnov, D.N. Spergel, J.N. Bahcall	(IAS+)
VIDYAKIN	94	JETPL 59 390	G.S. Vidyakin *et al.*	(KIAE)
		Translated from ZETFP 59 364.		
VILAIN	94C	ZPHY C64 539	P. Vilain *et al.*	(CHARM II Collab.)
ALSTON-...	93	PRL 71 831	M. Alston-Garnjost *et al.*	(LBL, MTHO+)
ARTEMEV	93	JETPL 58 262	V.A. Artemiev *et al.*	(ITEP, INRM)
		Translated from ZETFP 58 256.		

BAHRAN	93	PR D47 R754	M. Bahran, G.R. Kalbfleisch	(OKLA)
BAHRAN	93B	PR D47 R759	M. Bahran, G.R. Kalbfleisch	(OKLA)
BARANOV	93	PL B302 336	S.A. Baranov *et al.*	(JINR, SERP, BUDA)
BERNATOW...	93	PR C47 806	T. Bernatowicz *et al.*	(WUSL, TATA)
FREEDMAN	93	PR D47 811	S.J. Freedman *et al.*	(LAMPF E645 Collab.)
GRUWE	93	PL B309 463	M. Gruwe *et al.*	(CHARM II Collab.)
KALBFLEISCH	93	PL B303 355	G.R. Kalbfleisch, M.Y. Bahran	(OKLA)
KAWASHIMA	93	PR C47 R2452	A. Kawashima, K. Takahashi, A. Masuda	(TOKYC+)
MORTARA	93	PRL 70 394	J.L. Mortara *et al.*	(ANL, LBL, UCB)
OHSHIMA	93	PR D47 4840	T. Ohshima *et al.*	(KEK, TUAT, RIKEN+)
VUILLEUMIER	93	PR D48 1009	J.C. Vuilleumier *et al.*	(NEUC, CIT, VILL)
ABREU	92B	PL B274 230	P. Abreu *et al.*	(DELPHI Collab.)
BAHRAN	92	PL B291 336	M.Y. Bahran, G.R. Kalbfleisch	(OKLA)
BALYSH	92	PL B283 32	A. Balysh *et al.*	(MPIH, KIAE, SASSO)
BECKER-SZ...	92	PRL 69 1010	R.A. Becker-Szendy *et al.*	(IMB Collab.)
BECKER-SZ...	92B	PR D46 3720	R.A. Becker-Szendy *et al.*	(IMB Collab.)
BEIER	92	PL B283 446	E.W. Beier *et al.*	(KAM2 Collab.)
Also	94	PTRSL A346 63	E.W. Beier, E.D. Frank	(PENN)
BERNATOW...	92	PRL 69 2341	T. Bernatowicz *et al.*	(WUSL, TATA)
BLUM	92	PL B275 506	D. Blum *et al.*	(NEMO Collab.)
BORODOV...	92	PRL 68 274	L. Borodovsky *et al.*	(COLU, JHU, ILL)
BRITTON	92	PRL 68 3000	D.I. Britton *et al.*	(TRIU, CARL)
Also	94	PR D49 28	D.I. Britton *et al.*	(TRIU, CARL)
BRITTON	92B	PR D46 R885	D.I. Britton *et al.*	(TRIU, CARL)
ELLIOTT	92	PR C46 1535	S.R. Elliott *et al.*	(UCI)
HIRATA	92	PL B280 146	K.S. Hirata *et al.*	(Kamiokande II Collab.)
KAWAKAMI	92	PL B287 45	H. Kawakami *et al.*	(INUS, KEK, SCUC+)
KETOV	92	JETPL 55 564	S.N. Ketov *et al.*	(KIAE)
		Translated from ZETFP 55 544.		
MORI	92B	PL B289 463	M. Mori *et al.*	(KAM2 Collab.)
ALEXANDER	91F	ZPHY C52 175	G. Alexander *et al.*	(OPAL Collab.)
AVIGNONE	91	PL B256 559	F.T. Avignone *et al.*	(SCUC, PNL, ITEP+)
BELLOTTI	91	PL B266 193	E. Bellotti *et al.*	(MILA, INFN)
CASPER	91	PRL 66 2561	D. Casper *et al.*	(IMB Collab.)
DELEENER-...	91	PR D43 3611	N. de Leener-Rosier *et al.*	(LOUV, ZURI+)
EJIRI	91	PL B258 17	H. Ejiri *et al.*	(OSAK)
HIRATA	91	PRL 66 9	K.S. Hirata *et al.*	(Kamiokande II Collab.)
KUVSHINN...	91	JETPL 54 253	A.A. Kuvshinnikov *et al.*	(KIAE)
MANUEL	91	JP G17 S221	O.K. Manuel	(MISSR)
REUSSER	91	PL B255 143	D. Reusser *et al.*	(NEUC, CIT, PSI)
SATO	91	PR D44 2220	N. Sato *et al.*	(Kamiokande Collab.)
SUHONEN	91	NP A535 509	J. Suhonen, S.B. Khadkikar, A. Faessler	(JYV+)
TOMODA	91	RPP 54 53	T. Tomoda	
TURKEVICH	91	PRL 67 3211	A. Turkevich, T.E. Economou, G.A. Cowan	(CHIC+)
YOU	91	PL B265 53	K. You *et al.*	(BHEP, CAST+)
ADEVA	90S	PL B251 321	B. Adeva *et al.*	(L3 Collab.)
BATUSOV	90B	ZPHY C48 209	Y.A. Batusov *et al.*	(JINR, ITEP, SERP)
BERGER	90B	PL B245 305	C. Berger *et al.*	(FREJUS Collab.)
BURCHAT	90	PR D41 3542	P.R. Burchat *et al.*	(Mark II Collab.)
DECAMP	90F	PL B236 511	D. Decamp *et al.*	(ALEPH Collab.)
HIRATA	90	PRL 65 1297	K.S. Hirata *et al.*	(Kamiokande II Collab.)
JUNG	90	PRL 64 1091	C. Jung *et al.*	(Mark II Collab.)
MILEY	90	PRL 65 3092	H.S. Miley *et al.*	(SCUC, PNL)
STAUDT	90	EPL 13 31	A. Staudt, K. Muto, H.V. Klapdor-Kleingrothaus	
VASENKO	90	MPL A5 1299	A.A. Vasenko *et al.*	(ITEP, YERE)
VIDYAKIN	90	JETP 71 424	G.S. Vidyakin *et al.*	(KIAE)
		Translated from ZETF 98 764.		
ABRAMS	89C	PRL 63 2447	G.S. Abrams *et al.*	(Mark II Collab.)
AGLIETTA	89	EPL 8 611	M. Aglietta *et al.*	(FREJUS Collab.)
BAHCALL	89	Neutrino Astrophysics	J.N. Bahcall	(IAS)
Cambridge University Press				
BLUMENFELD	89	PRL 62 2237	B.J. Blumenfeld *et al.*	(COLU, ILL, JHU)
DAVIS	89	ARNPS 39 467	R. Davis, A.K. Mann, L. Wolfenstein	(BNL, PENN+)
ENQVIST	89	NP B317 647	K. Enqvist, K. Kainulainen, J. Maalampi	(HELS)
FISHER	89	PL B218 257	P.H. Fisher *et al.*	(CIT, NEUC, PSI)
MUTO	89	ZPHY A334 187	K. Muto, E. Bender, H.V. Klapdor	(TINT, MPIH)
OYAMA	89	PR D39 1481	Y. Oyama *et al.*	(Kamiokande II Collab.)
AFONIN	88	JETP 67 213	A.I. Afonin *et al.*	(KIAE)
		Translated from ZETF 94 1, issue 2.		

AKERLOF	88	PR D37 577	C.W. Akerlof et al.	(HRS Collab.)
AMMOSOV	88	ZPHY C40 487	V.V. Ammosov et al.	(SKAT Collab.)
BERGSMA	88	ZPHY C40 171	F. Bergsma et al.	(CHARM Collab.)
BERNARDI	88	PL B203 332	G. Bernardi et al.	(PARIN, CERN, INFN+)
BIONTA	88	PR D38 768	R.M. Bionta et al.	(IMB Collab.)
CALDWELL	88	PRL 61 510	D.O. Caldwell et al.	(UCSB, UCB, LBL)
DURKIN	88	PRL 61 1811	L.S. Durkin et al.	(OSU, ANL, CIT+)
ENGEL	88	PR C37 731	J. Engel, P. Vogel, M.R. Zirnbauer	
LOVERRE	88	PL B206 711	P.F. Loverre	(INFN)
OLIVE	88	PL B205 553	K.A. Olive, M. Srednicki	(MINN, UCSB)
SREDNICKI	88	NP B310 693	M. Srednicki, R. Watkins, K.A. Olive	(MINN, UCSB)
AFONIN	87	JETPL 45 257	A.I. Afonin et al.	(KIAE)
		Translated from ZETFP 45 201.		
AHLEN	87	PL B195 603	S.P. Ahlen et al.	(BOST, SCUC, HARV+)
AHRENS	87	PR D36 702	L.A. Ahrens et al.	(BNL, BROW, UCI+)
BELLOTTI	87	EPL 3 889	E. Bellotti et al.	(MILA)
BOEHM	87	Massive Neutrinos	A. Bohm, H. Vogel	(CIT)
Cambridge Univ.		Press, Cambridge		
BOFILL	87	PR D36 3309	J. Bofill et al.	(MIT, FNAL, MSU)
DAUM	87	PR D36 2624	M. Daum et al.	(SIN, VIRG)
GRIEST	87	NP B283 681	K. Griest, D. Seckel	(UCSC, CERN)
Also	88	NP B296 1034 erratum	K. Griest, D. Seckel	(UCSC, CERN)
LOSECCO	87	PL B184 305	J.M. LoSecco et al.	(IMB Collab.)
MISHRA	87	PRL 59 1397	S.R. Mishra et al.	(COLU, CIT, FNAL+)
OBERAUER	87	PL B198 113	L.F. Oberauer, F. von Feilitzsch, R.L. Mossbauer	
TALEBZADEH	87	NP B291 503	M. Talebzadeh et al.	(BEBC WA66 Collab.)
TOMODA	87	PL B199 475	T. Tomoda, A. Faessler	(TUBIN)
VIDYAKIN	87	JETP 66 243	G.S. Vidyakin et al.	(KIAE)
		Translated from ZETF 93 424.		
WENDT	87	PRL 58 1810	C. Wendt et al.	(Mark II Collab.)
ABRAMOWICZ	86	PRL 57 298	H. Abramowicz et al.	(CDHS Collab.)
AFONIN	86	JETPL 44 142	A.I. Afonin et al.	(KIAE)
		Translated from ZETFP 44 111.		
ALLABY	86	PL B177 446	J.V. Allaby et al.	(CHARM Collab.)
ANGELINI	86	PL B179 307	C. Angelini et al.	(PISA, ATHU, PADO+)
AZUELOS	86	PRL 56 2241	G. Azuelos et al.	(TRIU, CNRC)
BADIER	86	ZPHY C31 21	J. Badier et al.	(NA3 Collab.)
BERNARDI	86	PL 166B 479	G. Bernardi et al.	(CURIN, INFN, CDEF+)
BERNARDI	86B	PL B181 173	G. Bernardi et al.	(CURIN, INFN, CDEF+)
BRUCKER	86	PR D34 2183	E.B. Brucker et al.	(RUTG, BNL, COLU)
DORENBOS...	86	PL 166B 473	J. Dorenbosch et al.	(CHARM Collab.)
USHIDA	86C	PRL 57 2897	N. Ushida et al.	(FNAL E531 Collab.)
ZACEK	86	PR D34 2621	G. Zacek et al.	(CIT-SIN-TUM Collab.)
AFONIN	85	JETPL 41 435	A.I. Afonin et al.	(KIAE)
		Translated from ZETFP 41 355.		
Also	85B	JETPL 42 285	A.I. Afonin et al.	(KIAE)
		Translated from ZETFP 42 230.		
AHRENS	85	PR D31 2732	L.A. Ahrens et al.	(BNL, BROW, KEK+)
ALBRECHT	85I	PL 163B 404	H. Albrecht et al.	(ARGUS Collab.)
APALIKOV	85	JETPL 42 289	A.M. Apalikov et al.	(ITEP)
		Translated from ZETFP 42 233.		
BELIKOV	85	SJNP 41 589	S.V. Belikov et al.	(SERP)
		Translated from YAF 41 919.		
COOPER-...	85	PL 160B 207	A.M. Cooper-Sarkar et al.	(CERN, LOIC+)
COWSIK	85	PL 151B 62	R. Cowsik	(TATA)
MARKEY	85	PR C32 2215	J. Markey, F. Boehm	(CIT)
OHI	85	PL 160B 322	T. Ohi et al.	(TOKY, INUS, KEK)
STOCKDALE	85	ZPHY C27 53	I.E. Stockdale et al.	(ROCH, CHIC, COLU+)
ZACEK	85	PL 164B 193	V. Zacek et al.	(MUNI, CIT, SIN)
BALLAGH	84	PR D30 2271	H.C. Ballagh et al.	(UCB, LBL, FNAL+)
BERGSMA	84	PL 142B 103	F. Bergsma et al.	(CHARM Collab.)
CAVAIGNAC	84	PL 148B 387	J.F. Cavaignac et al.	(ISNG, LAPP)
DYDAK	84	PL 134B 281	F. Dydak et al.	(CERN, DORT, HEIDH, SACL+)
FREESE	84	NP B233 167	K. Freese, D.N. Schramm	(CHIC, FNAL)
GABATHULER	84	PL 138B 449	K. Gabathuler et al.	(CIT, SIN, MUNI)
HAXTON	84	PPNP 12 409	W.C. Haxton, Stevenson	
MINEHART	84	PRL 52 804	R.C. Minehart et al.	(VIRG, SIN)
SCHRAMM	84	PL 141B 337	D.N. Schramm, G. Steigman	(FNAL, BART)
STOCKDALE	84	PRL 52 1384	I.E. Stockdale et al.	(ROCH, CHIC, COLU+)
AFONIN	83	JETPL 38 436	A.I. Afonin et al.	(KIAE)
		Translated from ZETFP 38 361.		
BELENKII	83	JETPL 38 493	S.N. Belenky et al.	(KIAE)
		Translated from ZETFP 38 406.		

BELIKOV	83	JETPL 38 661	S.V. Belikov *et al.*	(SERP)
		Translated from ZETFP 38 547.		
BERGSMA	83	PL 122B 465	F. Bergsma *et al.*	(CHARM Collab.)
BERGSMA	83B	PL 128B 361	F. Bergsma *et al.*	(CHARM Collab.)
BRYMAN	83B	PRL 50 1546	D.A. Bryman *et al.*	(TRIU, CNRC)
Also	83	PRL 50 7	D.A. Bryman *et al.*	(TRIU, CNRC)
DEUTSCH	83	PR D27 1644	J.P. Deutsch, M. Lebrun, R. Prieels	(LOUV)
GRONAU	83	PR D28 2762	M. Gronau	(HAIF)
KIRSTEN	83	PRL 50 474	T. Kirsten, H. Richter, E. Jessberger	(MPIH)
Also	83B	ZPHY 16 189	T. Kirsten, H. Richter, E.K. Jessberger	(MPIH)
SCHRECK...	83	PL 129B 265	K. Schreckenbach *et al.*	(ISNG, ILLG)
TAYLOR	83	PR D28 2705	G.N. Taylor *et al.*	(HAWA, LBL, FNAL)
COOPER	82	PL 112B 97	A.M. Cooper *et al.*	(RL)
HAYANO	82	PRL 49 1305	R.S. Hayano *et al.*	(TOKY, KEK, TSUK)
OLIVE	82	PR D25 213	K.A. Olive, M.S. Turner	(CHIC, UCSB)
VUILLEUMIER	82	PL 114B 298	J.L. Vuilleumier *et al.*	(CIT, SIN, MUNI)
ABELA	81	PL 105B 263	R. Abela *et al.*	(SIN)
ARMENISE	81	PL 100B 182	N. Armenise *et al.*	(BARI, CERN, MILA+)
ASANO	81	PL 104B 84	Y. Asano *et al.*	(KEK, TOKY, INUS, OSAK)
Also	81	PR D24 1232	R.E. Shrock	(STON)
ASRATYAN	81	PL 105B 301	A.E. Asratyan *et al.*	(ITEP, FNAL, SERP+)
BAKER	81	PRL 47 1576	N.J. Baker *et al.*	(BNL, COLU)
Also	78	PRL 40 144	A.M. Cnops *et al.*	(BNL, COLU)
BERNSTEIN	81	PL 101B 39	J. Bernstein, G. Feinberg	(STEV, COLU)
BOLIEV	81	SJNP 34 787	M.M. Boliev *et al.*	(INRM)
		Translated from YAF 34 1418.		
CALAPRICE	81	PL 106B 175	F.P. Calaprice *et al.*	(PRIN, IND)
DEDEN	81	PL 98B 310	H. Deden *et al.*	(BEBC Collab.)
ERRIQUEZ	81	PL 102B 73	O. Erriquez *et al.*	(BARI, BIRM, BRUX+)
KWON	81	PR D24 1097	H. Kwon *et al.*	(CIT, ISNG, MUNI)
NEMETHY	81B	PR D23 262	P. Nemethy *et al.*	(YALE, LBL, LASL+)
SHROCK	81	PR D24 1232	R.E. Shrock	(STON)
SHROCK	81B	PR D24 1275	R.E. Shrock	(STON)
SILVERMAN	81	PRL 46 467	D. Silverman, A. Soni	(UCI, UCLA)
USHIDA	81	PRL 47 1694	N. Ushida *et al.*	(AICH, FNAL, KOBE, SEOU+)
AVIGNONE	80	PR C22 594	F.T. Avignone, Z.D. Greenwood	(SCUC)
BOEHM	80	PL 97B 310	F. Boehm *et al.*	(ILLG, CIT, ISNG, MUNI)
FRITZE	80	PL 96B 427	P. Fritze	(AACH3, BONN, CERN, LOIC, OXF+)
REINES	80	PRL 45 1307	F. Reines, H.W. Sobel, E. Pasierb	(UCI)
Also	59	PR 113 273	F. Reines, C.L. Cowan	(LASL)
Also	66	PR 142 852	F.A. Nezrick, F. Reines	(CASE)
Also	76	PRL 37 315	F. Reines, H.S. Gurr, H.W. Sobel	(UCI)
SHROCK	80	PL 96B 159	R.E. Shrock	(STON)
DAVIS	79	PR C19 2259	R. Davis *et al.*	(CIT)
BLIETSCHAU	78	NP B133 205	J. Blietschau *et al.*	(Gargamelle Collab.)
CROUCH	78	PR D18 2239	M.F. Crouch *et al.*	(CASE, UCI, WITW)
VYSOTSKY	77	JETPL 26 188	M.I. Vysotsky, A.D. Dolgov, Y.B. Zeldovich	(ITEP)
		Translated from ZETFP 26 200.		
BELLOTTI	76	LNC 17 553	E. Bellotti *et al.*	(MILA)
SZALAY	76	AA 49 437	A.S. Szalay, G. Marx	(EOTV)
SZALAY	74	APAH 35 8	A.S. Szalay, G. Marx	(EOTV)
COWSIK	72	PRL 29 669	R. Cowsik, J. McClelland	(UCB)
MARX	72	Nu Conf. Budapest	G. Marx, A.S. Szalay	(EOTV)
GERSHTEIN	66	JETPL 4 120	S.S. Gershtein, Y.B. Zeldovich	(KIAM)
		Translated from ZETFP 4 189.		